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ELECTRICAL ENGINEERING TESTS.

LABORATORY

AND

FACTORY TESTS

IN

ELECTRICAL ENGINEERING

BY

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AND

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SECOND EDITION
Thoroughly Revised and Enlarged

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PREFACE.

This book represents the laboratory work required in the Electrical Engineering Course at Columbia University. It is intended to serve as a text-book for the use of students, but furthermore it may be found useful by those who are engaged in the electrical profession.

In describing the various tests, brief discussions of the theory involved are given only when considered necessary, as a considerable knowledge of fundamental electrical principles is assumed on the part of the reader.

The authors desire to express their appreciation of the assistance and suggestions of S. M. Day and C. A. Schneider, late assistants in the Electrical Engineering Department.

G. F. S.
F. T.

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ELECTRICAL ENGINEERING TESTS.

Introduction.

In general testing it is not necessary to carry out a complete investigation on each machine after its type has been fully developed; in such a case only the most important or characteristic measurements are made. These are usually known as "commercial tests."

There are, however, many other tests which are special and only performed when it is desired to investigate a machine quite fully. In addition to these a number of experiments have been described whose object is to illustrate the properties and general characteristics of the machines to which they relate. The contents of this book may therefore be classified as follows:

	Commercial Tests.	Illustrative and Special Tests.
Part I.	4, 5, 7, 8, 10, 14, 15, 17, 19, 20, 21, 22, 25.	1, 2, 3, 6, 9, 11, 12, 13, 16, 18, 23, 24, 26.
Part II.	5, 7, 8 (b), 9, 10, 12, 13, 16, 17, 19, 30, 31.	1, 2, 3, 4, 6, 8 (a), 11, 14, 15, 18, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 32, 33, 34, 35, 36, 37, 38, 39, 40.

Part III. — It has been thought unnecessary to arrange the determinations described in this portion of the book in accordance with the classification above.

General Instructions.

Before commencing any experiment or test, its description should be carefully studied in order to obtain a clear understanding of its object and the method of procedure. By gaining a complete understanding of the purpose of an experiment or test

before commencing the actual work, a much more satisfactory comprehension of its results can be obtained. There is also less likelihood of taking unnecessary readings and omitting others of importance, thereby impairing the value of the results.

Engineering practice demands that a systematic record of all original observations be kept during the progress of a test. In order to follow this, all instrument readings should be placed in a note-book immediately upon being observed. It is advisable to prepare previously a tabulated form in which these observations can be entered, thereby insuring neatness and the recording of corresponding readings in such manner as will prevent confusion and error in deducing the final results. In the completed report the original data and deduced results should be entered and properly designated.

Presentation of Report.

An engineering report should be as complete as the circumstances demand, its workmanship should be neat, its opinions clear and concise and its statements exact, so that there can be no question as to the meaning conveyed. Drawings, diagrams and graphical representations of results should be executed in the best possible manner. An engineering report is often taken as a criterion of the ability of the engineer and therefore should demand from him his best endeavors.

The report of a test should include the following matter:

1. A clear statement of the object of the test with an explanation of the method of procedure.

2. A description of all the apparatus used.

(Designate all machines by their names, types and capacities and all instruments by their numbers, types and capacities. It is important to note any errors due to the displacement of the pointer or needle of the measuring instruments.)

3. All original observations and data. All deduced results. All important calculations in detail. Curves (when necessary) illustrating graphically the relation existing between the various quantities.

If original observations and deduced results are capable of such arrangement, they should be neatly tabulated.

4. Conclusions deduced from the results of the test and the reasons leading up to these should always be included.

5. A diagram or diagrams of the arrangement of all apparatus, including electrical connections, the various pieces of apparatus being properly designated by letter or name.

Instructions for Plotting Curves.

Curves are employed to illustrate graphically the relations which exist between the values of two variable quantities. The values of one quantity are used as the ordinates while the corresponding values of the other are used as the abscissas of the curve.

In order that the curve may properly represent the correct relation of the two variables, it is necessary to select a proper ratio between the scales of the ordinates. It is most important always to consider the possible per cent. error involved in the determination of any quantity. Entirely on this depends the scale selected for the representation of the results. A good rule is to make the distances on the cross-section paper approximately of the same order as the length of arc of the instrument reading.

A curve need not follow exactly the observed or calculated points, but will usually follow a mean path through these points. Any point departing widely from this average path is probably an error in observation and it may be necessary to go over that part of the work to ascertain whether or not this point is actually an error or a characteristic of the phenomena under investigation. The curve which expresses the relation between two uniformly varying variable quantities is a smooth one and any point departing widely from its path is undoubtedly plotted from an incorrect observation.

Use of Instruments and Machines.

Before connecting the instruments to a circuit, adjust the quantities to be measured — current, pressure or power — to such

values that they lie within the capacity of the instruments to be used. If this precaution is not taken, the pointer or needle is liable to be bent and the instrument, especially in the case of a voltmeter, to be burned out.

Instruments should not be used in close proximity to dynamos, motors or conductors carrying large currents, for readings are affected by magnetic leakage from these sources, and the steel magnets in the instruments are liable to be permanently changed. A certain method of detecting this trouble is to note whether the instrument reads the same when it is turned around into different angular positions.

When instruments are placed upon tables or benches, the conductors leading to them should be secured to some point so that the instruments may not be pulled off and so suffer damage by falling upon the floor.

Do not handle instruments *roughly*, for such treatment is liable to dull the pivots or break the jewels which form the bearings.

When using any instruments with metallic covers do not allow the conductors to touch the cover, for the needle of these instruments may be connected to one side of the circuit and if wires from the other side should make contact with the cover, a short circuit may be caused by the needle touching the cover at the end of its swing.

When instruments are left continuously in circuit, the heating error comes in and must be allowed for.

When using a voltmeter and an ammeter for measuring the resistance of an *inductive circuit*, always *disconnect* the *voltmeter before* opening the circuit, otherwise the inductive discharge will injure the instrument.

General Directions for Operating Machines.

Before starting a dynamo or a motor make sure that there are no obstructions in the air gap or elsewhere, that the pulley is securely fastened to the shaft, that the belt is tight enough, that

the machine has been properly and securely set up, and that the oil stands at the proper height in the gauges.

The wiring for the test should be so disposed that the wires do not touch each other, and that they are insulated from the frame of the machine or the floor, if that is of iron. All joints in the cables must be carefully wrapped, and no opportunity left for a ground or a short circuit.

In starting the machine allow it to revolve for a time at about half speed and see that each oil ring is acting satisfactorily.

In the case of a direct current motor particular care must be taken to tie down the wires leading to the field so that they cannot be pulled out accidentally. The field should always be excited from the same dynamo that is to supply the armature. Before starting the motor it is necessary to make sure that the full field strength is present, either by slightly opening the field switch and noting the inductive discharge, or by testing the poles with a piece of iron. Never open a field circuit without first cutting in the full resistance of the rheostats so as to diminish the inductive discharge at the break.

Never vary a field resistance quickly, as this will cause a sudden rush of current in the armature circuit which may open a circuit breaker, or even break a belt, if it does not cause it to fly off the pulley.

Always close a switch strongly, sending the handle down sharply and as far as it will go; the result of this is that in the case of a short circuit on the line the circuit breaker will probably open without further incident.

During a test, watch the temperature of the bearings as one of them will often heat up quite rapidly; a bearing is getting too hot when you can no longer hold your hand on it.

When in charge of a test, be sure, when starting the machines, that you have a thoroughly clear idea of the wiring so that in case of accident you will know at once what steps to take.

Never close a circuit breaker without first seeing that there is an open switch in series with it.

In all kinds of testing the determination of speed is one of the most difficult and probably also the most important, since on it depends the value of the readings of all the other instruments. The most convenient method of reading the speed is by means of a tachometer or speed indicator which must be carefully calibrated with a speed counter before it is used; indeed too much care cannot be exercised here, as an error in this calibration renders all the subsequent work useless.

When using a tachometer the man in charge of the test should first find out if the speed is right and then give the signal for all the others to read the instruments to which they are assigned, It is desirable if possible to assign one man to each instrument.

When speed counters are used the speed should be taken for one minute, during which entire time each man must carefully watch the instrument he is reading, and estimate the average value. The disadvantages of this method are that it is slow and tedious, and if the test is a complicated one the probability of a break down in some part of the outfit is greatly enhanced. On the other hand each reading is independent of all the others, and the chances are good that the majority of them will be correct.

Table of Symbols.

The recommendations of the international congresses and the Standardization Report of the American Institute of Electrical Engineers have been adopted in forming the following table of symbols.

At = ampère turns.

B = magnetic induction in lines of force per unit area.

b = breadth, width.

γ = electrical conductivity.

C = capacity.

D, d = diameter.

E, e = electromotive force, voltage, potential difference.

ϵ = eddy current coefficient.

f = frequency.

F = magnetomotive force, in *Gilberts*. M.M.F.

F, f = force or pull in pounds or kilograms.

Φ = total magnetic flux in magnetic circuit under consideration, in *Webers*.

H = magnetizing force or M.M.F. per unit length, in *Gausses*.

$= \frac{\mathsf{F}}{l}$.

h = height or thickness.

HP = horse-power.

η = hysteresis factor.

Eff = commercial efficiency.

I_{se} = current in series field.

I_{sh} = current in shunt field.

I_f = total current in fields.

I_t = total current delivered to or by a machine.

J = Joule's mechanical equivalent of heat.

K = constant.

L, l = length or distance.

L = Inductance in henrys.

M = mass or volume.

μ = magnetic permeability.

N = number of revolutions per minute.

n = number of inductors in series on armature.

P = pull or force in pounds.

p = number of pairs of poles.

R = reluctance (magnetic resistance) of magnetic circuit, in *Oersteds*.

R = electrical resistance, in *Ohms*.

S = surface or area.

T = time.

t = temperature.

T = torque or turning moment in ft. lbs.

v = velocity, linear speed.

W, wt = weight.

X = reactance.

Z = impedance.

General Equations.

Electrical Circuits.—

Ohm's law is as follows: "The strength of the current varies directly as the electromotive force and inversely as the resistance of the circuit" or

$$I = \frac{E}{R}.$$

Also

$$E = IR, \quad R = \frac{E}{I},$$

$I =$ current in *ampères*,

$E = E.M.F.$ in *volts*.

$R =$ resistance in *ohms*.

The resistance (R) of a conductor varies directly as its length (l) and inversely as its cross-section (S) and conductivity (γ); or $R \propto l/S\gamma$.

The power or rate of expenditure of energy, in *watts* or *kilowatts*, in any electrical circuit carrying direct current, is $P = IE = I \times IR = I^2R =$ watts.

1 $HP = 746$ watts.

1 kilo-watt $= 1.34$ HP.

The amount of energy in the form of heat expended in a circuit in (T) seconds is measured in *Calories*. Denoting time in seconds by (T) and Joule's mechanical equivalent of heat by (J) we have,

$$\text{Heat in calories} = \frac{I^2RT}{J}$$

$$J = 4.2 \times 10^7 \text{ ergs}.$$

Magnetic Circuits.—

$$\text{Flux } (\Phi) = \frac{\text{Magnetomotive force } (\mathbf{F})}{\text{Reluctance } (\mathbf{R})},$$

Magnetomotive force ($\mathbf{F}$) = Flux (Φ) $\times$ Reluctance ($\mathbf{R}$),

$$\mathbf{F} = \frac{4\pi}{10} At, \quad \mathbf{R} = \frac{\text{length of path of flux}}{\text{area} \times \text{permeability}} = \frac{l}{S\mu},$$

$$\Phi = \frac{4\pi}{10} At \div \frac{l}{S\mu} = \frac{4\pi}{10} \frac{AtS\mu}{l},$$

$$\frac{\Phi}{S} = \text{Density } (\mathbf{B}) = \frac{4\pi}{10} \frac{At\mu}{l},$$

$$\mathbf{H} = \text{magnetizing force} = \frac{4\pi}{10} \cdot \frac{At}{l},$$

Then

$$\frac{\mathbf{B}}{\mathbf{H}} = \frac{4\pi}{10} \frac{At\mu}{l} \div \frac{4\pi}{10} \frac{At}{l} = \text{permeability} = \mu.$$

Equations for E.M.F. of a Dynamo.
E is proportional to ΦNn.

$E = \dfrac{2\Phi Nnp}{60 \times 10^8 \times c}$ where Φ = flux entering armature from one pole.

$\dfrac{N}{60}$ = no. revolutions per second.

n = total no. of inductors on armature.

p = pairs of poles, being 1 for a bipolar machine.

c = no. of circuits in parallel on armature.

$\dfrac{Np}{60}$ = no. of cycles per second or frequency f.

Equations for a Motor.—

$$I = \frac{E - e}{R}, \qquad E = e + IR, \qquad e = E - IR,$$

in which

E = E.M.F. at motor terminals.
e = counter E.M.F. of armature in *volts.*
I = current in armature in *ampères.*
I_f = current in fields of motor.

I_t = total current $= I + I_f$.
$I_t \times E$ = power in *watts* delivered to motor.
$I_f \times E$ = power expended in fields.
$I \times E$ = power delivered to armature.
$I \times e$ = power developed in armature.

$$\frac{I \times e - \text{stray power losses}}{I_t \times E} = \text{commercial efficiency of machine.}$$

The *torque* or turning effort of a motor depends upon the armature current, number of armature inductors and flux through the armature. It is independent of the speed.

Proof:

$$HP = \frac{2\pi LFN}{33\,000} = \frac{eI - K}{746}.$$

F = force exerted at radius L.

$\therefore FL$ = turning moment or torque.

e = counter E.M.F. of armature.

$$e = \frac{2\Phi Nnp}{60 \times 10^8 \times c}.$$

$$\therefore \frac{2\pi LFN}{33\,000} = \frac{2\Phi NnpI - K}{746 \times 60 \times 10^8 \times c}.$$

$$\text{Torque} = LF = \frac{(2\Phi NnpI - K)33\,000}{2\pi N 746 \times 60 \times 10^8 \times c}.$$

$$\mathrm{T} = \Phi IK'.$$

TABLE OF EQUIVALENTS.*

Reduction to and from C. G. S. Units.

In the column headed "Reciprocals" the numbers are the factors for reducing from C. G. S. to English values.

Length.

	Cm.	Reciprocals.
1 inch =	2.54	.3937
1 foot =	30.48	.032809
1 mile =	160 933.	6.2138×10^{-6}

Area.

	Sq. cms.	
1 sq. inch =	6.4515	.1550
1 sq. foot =	929.01	.001076
1 sq. mile =	2.59×10^{10}	3.861×10^{-11}

Volume.

	Cu. cms.	
1 cu. inch =	16.387	.06102
1 cu. foot =	28 316.	3.532×10^{-5}
1 gallon =	4 541.	.0002202

Mass.

	Gram.	
1 grain =	.064799	15.432
1 ounce Avoirdupois =	28.3495	.035274
1 pound =	453.59	.0022046

Velocity.

	Cms. per Second.	
1 foot per sec.	= 30.48	.032809
1 mile per hour	= 44 704	.022369
1 kilometer per hour	= 27.777	.036

Density.

	Gm. per cu. cm.	
1 grain per cu. inch =	.00395438	252.88
1 pound per cu. foot =	.016019	62.426

The value of g is assumed to be equal to 981.

Force.

	Gm.	Dynes
1 poundal =	14 09	13 825.
1 pound =	453.59	4.45×10^5
1 grain =	.064799	63.6
1 kilogram =	10^3	9.81×10^5

Stress.

	Gm. per sq. cm.	Dynes per sq. cm.
1 lb per sq. foot	= .48826	479.
1 lb per sq. inch	= 70.31	69 000.
1 ton† per sq. inch	= 1.406×10^5	1.380×10^8

Work and Energy.

	Gm—cms.	Ergs.
1 foot pound	13 825.	1.3562×10^7
1 foot poundal =	4.3×10^2	4.2139×10^5
1 kilogrammeter =	10^5	9.81×10^7
1 Joule	1.109×10^4	10^7

Rate of Working.

	Gm—cms. per sec.	Ergs per sec.
1 horse power	= 7.604×10^6	7.46×10^9
1 force-de-cheval =	7.5×10^6	7.36×10^9
1 kilowatt	= 1.019×10^7	10^{10}
1 watt	= 1.019×10^4	10^7

(1 *horse power* = 746. *watts.*)

Mechanical Equivalent of Heat.

	Gm. cms.	Ergs.
1 gm. through 1°C.	= 4.281×10^4	4.2×10^7
1 pound " 1°C.	= 1.942×10^7	$1\ 905 \times 10^{10}$
1 " " 1°F.	= $1\ 079 \times 10^7$	1.058×10^{10}

(*1 gm. through 1°C. = 1 Calorie = 4.2 Joules.*)

† 2000 lbs.

* Everett C. G. S. System of Units.

PART I.

Direct Current Tests.

Experiment 1. — "Fall of Potential" or "Drop" along an Electrical Conductor.

This experiment is intended to prove the law that when a current of electricity flows through any metallic conductor, there is a loss of electrical potential along the conductor. This loss is proportional to the strength of the current and to the length of the conductor, assuming it to be of uniform size and conductivity throughout its length.

The resistance of a conductor varies directly as its length, and inversely as its area and conductivity $R \propto l/S\gamma$. If the area and conductivity remain constant under any given conditions, the resistance will vary directly as the length. By Ohm's law $E = IR$. $\therefore$ If the current in a conductor remains constant, the difference of potential along the wire will vary directly as the length.

TABLE I.

		Voltmeter Readings.								
		Copper			German Silver			Iron.		
Amperes		1.	3.	5.	1.	3.	5.	1.	3.	5.
Lengths in Inches	6.									
	12.									
	18.									
	24.									
	30.									
	36.									
	42.									
	48.									

Over equal lengths of conductor there will be equal differences of potential and if twice the length of conductor is included between the voltmeter terminals, the voltmeter will give a reading twice as large as before.

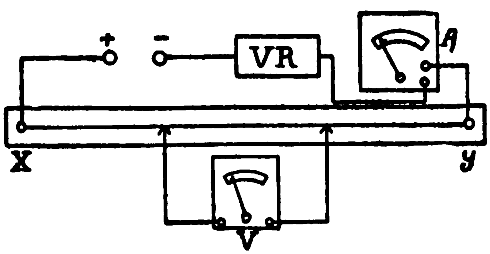
Method.—In order to prove this, a current may be passed through a conductor and by means of a voltmeter the differences of potential between points along the wire at uniform distances apart can be measured. Record these distances and the corresponding voltmeter readings. An ammeter should be inserted in the circuit, as shown in Fig. 1, in order that the current strength may be kept constant throughout the experiment.

Attach one voltmeter terminal to one end of the resistance and take readings along the wire at uniform intervals, the current remaining constant. This will show the uniform variation in potential along the wire. Note and record the results as shown in Table I.

After taking this set of readings alter the current and take a set of readings similar to the first. This will illustrate the proportionate variation in the drop with change in current.

Connections are as shown in Fig. 1 in which (x, y) is the conductor; (VR) is the variable resistance used to regulate the cur-

Fig. 1.



rent; (V) is the voltmeter to measure the fall of potential; (A) is the ammeter to measure the current, and (+, —) is the source of power.

Report.—The report of this experiment should contain, besides the conclusions, a curve sheet, showing the relation between volt-

meter readings and lengths of conductor; voltmeter readings to be plotted as ordinates, lengths as abscissas.

Experiment 2. — Measurement of the Resistance of a Conductor by the "Fall of Potential" or "Drop" Method.

(*a*) The "fall of potential" or "drop" method of measuring the resistance of a conductor is identical with the foregoing experiment. A known current is passed through the conductor whose resistance is required and by means of a voltmeter the difference of potential between the ends of the conductor is measured. Then the resistance may be calculated by Ohm's law in the form

$$R = \frac{E}{I}$$

Method. — In this manner the resistance of two coils of copper wire can be determined, using different values of current. The low reading scale of a Weston voltmeter can be used for the measurement of the "drop" between the ends of the wire if it is of low resistance and the "drops" are small. Any change in resistance due to change in temperature should be noted.

Report.—Tabulate results as in Table II. The connections are the same as in Fig. 1.

TABLE II.

Resistances of ---- and ---- .

	A.		B.		A+B Measured.		A+B Calculated.
Amperes	Drop.	Ohms.	Drop.	Ohms.	Drop.	Ohms.	Ohms.
5.							
10.							
	Difference-		Diff.-		Diff.-		

(*b*) Also determine the current, cold and hot resistance, total watts and watts per candle power for a 16- and a 32-candle power 115-volt lamp. Use Wheatstone bridge for the measurement of the cold resistance. Tabulate readings as in Table III. and draw conclusions.

TABLE III.

Candle Power.	Volts.	Current	Watts.	Watts per C.P.	Resistance	
					Hot	Cold.
16.						
32.						

Experiment 3.—Effect of Temperature Variation upon the Resistance of Metallic Conductors. Determination of Temperature Coefficients.

Electrical energy may be employed to do work of various kinds such as magnetic, mechanical, chemical and thermal. In doing any of these, part of the energy is wasted so far as any useful purpose is concerned, this following from the fact that the conversion of energy from one form to another cannot take place without some waste of energy. That which is wasted is converted into heat and is transferred to other bodies by radiation, conduction and convection.

When an electric current is transmitted by a conductor, resistance is offered to its passage. The result is that in forcing the current over the resistance a certain amount of energy is used, thereby developing heat in the conductor. When the resistance is high and a large amount of current has to be transmitted along the wire, the loss becomes large.

If the length and cross-section of two conductors of different materials are the same, the temperature developed will depend entirely upon the specific resistance of the materials. As the specific resistance of copper is lower than that of all metals except silver, and its price is not prohibitive, it has become the recognized material for use in electrical apparatus. Iron has about 0.16 and German silver about .06 the conductivity of copper.

Joule found by experiment that the number of heat units developed in an electrical conductor was directly proportional to the resistance, the square of the current and the time of passage of the current. Joule's law can be expressed as follows:

Heat in calories $= I^2RT \times 0.24$.

$T =$ time in seconds.

As the resistance of metallic conductors increases with rise in temperature, the temperature of a conductor and the amount of energy dissipated by it will increase until the rate at which heat is developed due to the passage of the current is balanced by the rate of loss of heat by conduction, convection and radiation.

The resistance of copper changes with variation in temperature, the relation being represented approximately as follows:

$$R_t = R_{t'}[1 + .004(t_1 - t)].$$

$R_t =$ resistance when hot.

$R_{t'} =$ resistance before passage of current.

$t_1 =$ temperature ° C. when hot.

$t =$ temperature ° C. before passage of current.

Another manner of expressing this is that copper has a positive temperature coefficient of 0.4 per cent. per degree Centigrade.

Iron and other pure metals have approximately the same temperature coefficient as is given for copper.

Alloys such as German silver and manganin generally possess a smaller temperature coefficient than any of their component metals. German silver is an alloy of copper, zinc and nickel possessing a temperature coefficient of about 0.04 per cent. per degree Centigrade.

Manganin, an alloy of manganese, copper and nickel, possesses between 30° and 65° C. a mean temperature coefficient of zero.

Such alloys are especially suitable in making standards of resistance.

Method. — Measurement of resistance at different temperatures and determination of temperature coefficients.

The apparatus used in this experiment consists of a jar or tank containing copper, iron and German silver wires of equal length and cross-section. The jar or tank is filled with oil, which is stirred, so as to maintain a uniform temperature. An ammeter, voltmeter and thermometers are necessary.

The three coils, the ammeter and a variable resistance are connected in series across the current supply, and current in suitable increments, is passed through this circuit. After any change in the current, ample time must elapse for the bath to reach its final temperature, and before any measurements of the resistance of the coils are made. The "drops" across the three coils are measured by means of a voltmeter, simultaneous readings of these, the currents and the temperatures being made.

From the ammeter and voltmeter readings the resistances are to be determined.

To find the temperature coefficient, the change in resistance is divided by the corresponding change in temperature times the resistance at the commencement. This gives the variation in ohms per degree for each material.

$$\text{Temperature coefficient} = \frac{R_{t_1} - R_t}{(t_1 - t)R_t}.$$

In order to ascertain when the temperature of the bath has reached a stationary value after any change in the current, attach the voltmeter terminals to the ends of the iron coil and when the voltmeter reading becomes constant no further change in temperature may be expected. This is due to the fact that a change of temperature causes a change in resistance with a corresponding variation in the "drop." When the temperature becomes constant all other conditions become constant.

Approximate values for the temperature coefficients can be obtained by this method, it being necessary to employ apparatus of a much higher degree of delicacy to obtain reliable results.

Report. — The report is to contain curves showing the relation; *a*, between the current values in ampères, plotted as abscissas, and the calculated resistances in ohms of each material as ordinates; *b*, between ampères as abscissas and watts expended in heating each material as ordinates; *c*, between temperature values as abscissas and ohms of each material as ordinates. Draw conclusions.

Experiment 4. — Measurement of the Insulation Resistance of an Armature, Commutator and Field Coil.

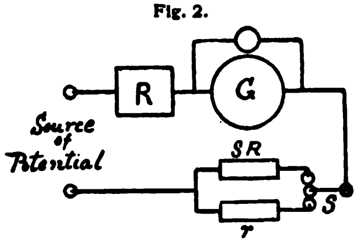
In all electrical apparatus it is necessary to provide suitable insulation between the current-carrying conductors and the parts or appliances which support them.

The insulation materials consist of cotton, silk, rubber, glass, porcelain, mica, paper and wood. Cotton, silk, mica and paper are used extensively on all electrical machinery and apparatus, rubber and paper for overhead and underground wires and cables, while glass and porcelain are used for the support of wires and in forming many electrical appliances. Wood has only a limited use, it being displaced by glass and porcelain on account of the fire risk.

The insulation resistance of an armature, commutator or field coil is the resistance between the material composing the electrical circuit and the supporting framework. In an armature it is the resistance between the wire and the core; in a commutator between the individual bars as well as between each bar and the shell; in a field coil between the wire and the frame on which it is wound.

Increase of exposed surface and temperature diminishes the actual value of the resistance, so that in many instances it is important to know the value of both these factors. This is especially necessary in determining the insulation resistance of a cable for submarine or underground use.

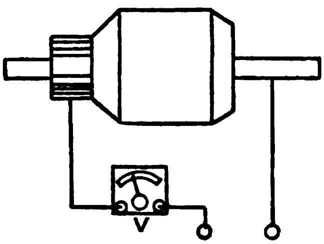
Fig. 2.



Method. — In the case of dynamo electric machinery where high voltages are employed, it is necessary to provide a high degree of insulation. Its value can be determined by the following method; a galvanometer with its shunt is placed at G as shown in Fig. 2; SR is known high resistance, r the insulation resistance to be measured. R a resistance permanently in the circuit to protect the G. The switch at S is first connected to

SR and the deflection of the *G* noted. Then *S* is connected to r and the deflection noted. If these are the same, r has the same resistance as *SR*. If the readings are not the same r can be calculated from the proportion $r : SR = d_{SR} : d_r$. In this method of measurement it is necessary to use a potential equal to that at which the apparatus is designed to operate. A higher potential will show a lower insulation resistance due to the fact that there may be more surface- and interior-leakage.

Fig. 3.



A modification of this method and the one commonly employed is to use a high resistance voltmeter as a combined galvanometer and resistance. This is placed in circuit as shown in Fig. 3. The voltage of the testing circuit is first measured by the voltmeter.

Then the source of potential is connected to the part to be measured with the voltmeter in series. If there is any fault or poor insulation a deflection of the needle will be indicated. By means of this deflection, the resistance of the voltmeter and the known voltage, the insulation resistance can be calculated as follows: let

$E =$ voltage of testing circuit.
$R =$ insulation resistance.
$d =$ observed deflection.
$r =$ resistance of voltmeter.

Deflection when the voltmeter only is in circuit is E; deflection when voltmeter and insulation are in circuit $= d$. Then we have the proportion $(R + r) : r = E : d$

$$(R + r)d = Er$$

$$R = \frac{Er}{d} - r$$

$$\therefore R = r\left(\frac{E}{d} - 1\right).$$

With the voltmeter method and the voltage available it may be that no deflection is noted; this simply indicates that there is no trouble with the part under test that would prevent its operation on the proper circuit. If there is no deflection, it does not show that the insulation resistance is infinity, but that the insulation is good and that the voltage used is not sufficient to give quantitative results.

Under *no circumstances use the low reading coils of a Weston or similar voltmeter* in this test, for if there is any defect in the insulation, the full potential of the circuit will be placed across the voltmeter causing damage to the instrument.

Do not hold bare contact terminals in the hand for the body may form part of the circuit and alter the results considerably.

Report.— Report to contain determinations of resistance made on an armature, commutator and field coil.

Determine resistance of self by using an E.M.F. of not over 115 volts and include results in report.

Experiment 5.—Measurement of Armature Resistance by (a) the "Drop" Method and (b) by Comparison with a Standard Resistance. (c) Measurement of the Resistance of a Shunt Field Coil by means of a Wheatstone Bridge.

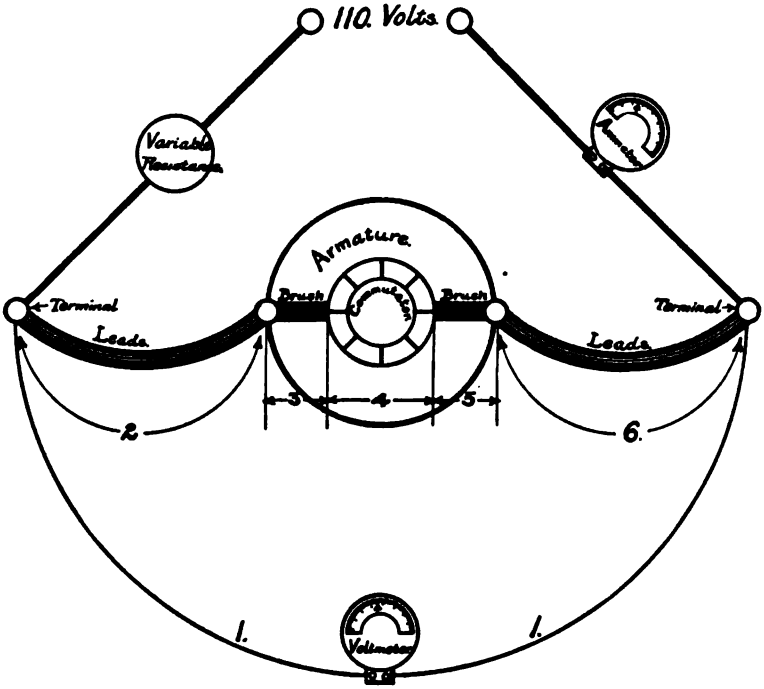
Owing to the comparatively low resistance of armatures it is generally impossible to obtain satisfactory results in the measurement of their resistances by the use of an ordinary Wheatstone bridge and a galvanometer. The armature resistance is made low in order that the energy wasted in this part of a dynamo or motor may be as small as is consistent with the size and design of the machine, and also to obtain good inherent regulation of potential in a dynamo and speed in a motor.

The resistance of an armature circuit is composed of the resistance of the conductors themselves, the brush contacts, that is the resistance of the surface contact between the copper or carbon brushes and the commutator (in the case of carbon brushes this may amount to an appreciable value), and the leads or cables from the machine terminals to the brush holder studs. The last is usually of small amount.

Methods. — There are two convenient and accurate methods for determining such low resistances, one employing the measurement of current and potential, the other of potential only. Calibrated standard commercial instruments are of sufficient accuracy for the measurements.

(*a*) *First.* — Pass through a circuit composed of an armature, an

Fig. 4.



ammeter and a variable resistance, a current which will produce a sensible "drop" or difference of potential across the different parts of the armature circuit (Fig. 4). These "drops" can then be measured by means of a low reading voltmeter, whose terminals can be transferred from one part of the circuit to another. The deflections on both instruments should be large in order to secure accuracy in the results. The resistance of any part can be calcu-

lated by Ohm's law, the current and E.M.F. being known. Show results as in Table IV.

TABLE IV.

Current in Amperes	Drops							Difference bet. 1 & 7	Ohms							Difference bet. 1 & 7
	1.	2.	3.	4.	5.	6.	7.		1.	2.	3.	4.	5.	6.	7.	

By this method the resistance of the *armature leads* (2 and 6), *brush contacts* (3 and 5) and *armature* (4) itself can be determined, it being advisable to take a number of sets of readings with different values of the current in order to eliminate errors and variations. (7) is the total calculated drop $= 2 + 3 + 4 + 5 + 6$.

It will be found in the case of machines with carbon brushes, that the brush contact resistance varies with the variation in the current used, being lower for the larger values of the current. Nothing of an absolutely definite nature regarding this resistance can be obtained in this manner, but some idea can be had of the importance of this resistance in dynamo and motor designing and testing.

In case the E.M.F. of the current supply is so high that too large a current would be sent over the resistance of the armature circuit, if connected directly to this E.M.F., it will be necessary to insert a variable resistance to regulate the strength of the current to the proper value for the machine under test. Do not allow the armature to rotate when the measurements are being made, for a counter E.M.F. is generated, which decreases the current and causes an apparent increase in the resistance of the armature. If the armature is permitted to run in this way and without any field, it will tend to rise to a dangerous speed.

(*b*) *Second.* — In this method there is employed a *known resistance* of large current carrying capacity and possessing a low temperature coefficient. This latter quality insures a constant resist-

ance with a varying temperature of the material. The standard is placed in series with the armature circuit and a controlling rheostat. A current of suitable strength is passed through the circuit (it is not necessary to measure this current) and the E.M.F.'s across the armature, brush contacts and armature cables, as in (*a*), and the standard resistance are recorded. The ratio of these "drops" will be equal to the ratio of the two resistances, or

$$E' : E = R' : R,$$

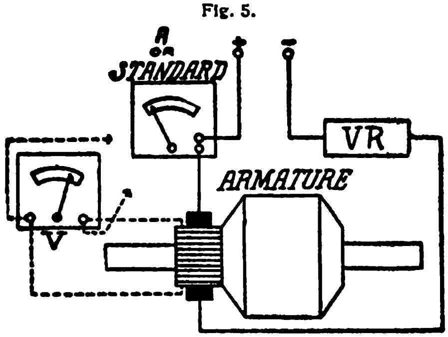
or

$$R' = \frac{E' \times R}{E},$$

E' = drop across the unknown resistance (armature, etc.).
E = drop across the standard resistance.
R' = value of unknown resistance (armature, etc.).
R = known resistance of standard.

This method possesses the advantage of requiring only one

Fig. 5.



measuring instrument with all readings of the same order. The resistance of the standard being once known and not liable to alteration removes one possibility of error. In the first method an ammeter would have to be calibrated or tested for every important measurement. In Fig. 5 is given a diagram of connections, the standard resistance being substituted for the ammeter in the second method.

When determining the drop in the armature, connect the voltmeter leads to segments, which are under brushes of opposite polarity. Be careful not to touch the terminals of the leads against the brushes while taking this drop. To determine brush drop, connect one voltmeter lead to brush stud. Hold the other on the segment on which that brush rests. Be careful not to touch the terminal on the segment against the brush while taking the brush drop.

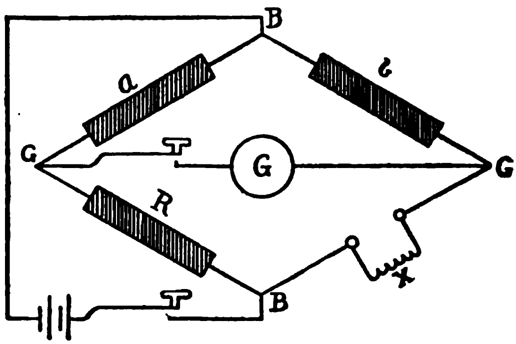
Report. — The report is to contain readings and results by both methods on the same apparatus.

Note. — These methods are applicable to the measurement of all metallic conductors of low resistance. Among the latter are included field coils, rheostats and wires of distributing systems.

(c) Measurement of Resistance of a Shunt Field Coil by means of a Wheatstone Bridge.

Wheatstone's bridge, or balance is an arrangement of resistances, typically represented in Fig. 6. *a* and *b* are two sets of coils, usually in the ratio 1 : 10 : 100 : 1000.

Fig. 6.



Suitable plugs permit the use of any coil at pleasure.

R is a set of coils, usually running from 1 to 10 000 ohms, so arranged that any number of units from 1 to 10 000 may be introduced into the circuit.

X is the unknown resistance to be measured.

In using the apparatus, a battery is connected to the points

(B, B), and a sensitive galvanometer to the points (G, G), as shown. A key is usually included in the battery circuit and another in the galvanometer circuit. These keys normally stand open.

The unknown resistance being connected as shown, a coil in each of the sets a and b, either equal or having the ratio of 1 to 10, 100 or 1000 is unplugged. The resistance R is then adjusted until the galvanometer suffers no deflection upon depressing the battery and galvanometer keys.

It may be easily shown that when the above condition obtains, the following relation exists between the four resistances:

$$\frac{a}{b} = \frac{R}{X}.$$

In Wheatstone bridge sets, as usually constructed, the resistances a, b, and R, consist of coils inclosed in a box and connected to terminals on the cover. Binding posts on the cover serve for connecting the battery, the galvanometer, and the unknown resistance. These binding posts are generally marked B, G, and X, respectively, the battery, of course, being connected to B, the galvanometer to G, and the unknown resistance to X. Sometimes the galvanometer is included in the set and is permanently connected inside the box.

Method.—To measure the resistance of a field coil, connect it to the posts marked X. Connect a battery of, say, three dry cells to the posts B, and a suitable galvanometer to the posts G, if the galvanometer is not already connected inside the box. Now, if there is nothing to indicate the value of the resistance to be measured, begin by unplugging equal resistance in a and b, say 100 ohms; then unplug any coil in R, depress the battery and then the galvanometer key, holding both down and note the direction in which the pointer moves. Now change R, making it much larger or smaller until a deflection in the opposite direction is obtained. The true value of X will then be somewhere between this first value and the last value of R.

Now beginning with a value that is known to be too large, vary the resistance in R systematically, trying each coil in succession

until one is found that is too small. Leaving this in circuit, try the smaller resistances in order, until a balance has been nearly obtained. Record this value of R.

If X proves to be a small resistance, its value should be determined to a fraction of an ohm; for this purpose, change the resistances in a and b, making a 10 times b; then obtain a new balance, beginning by making R 10 times as great as was required for the balance with a and b equal. Repeat, making a 100 times b.

Precautions. — If the galvanometer is of the magnetic needle type, it must be kept at some distance — several feet — from the field which is being measured; otherwise the needle will be deflected by the magnetism of the field.

It must be remembered that in consequence of self induction, the current in the field coil does not immediately reach its full strength upon closing the battery key. In other words, when the current begins in the coil, it is opposed by the self induction as well as by the true resistance, and the coil has an *apparent* resistance much greater than the true resistance. The true balance can only be obtained, therefore, by giving time after closing the battery key, for the current in the coil to become steady before closing the galvanometer key. This may require several seconds or, in large machines, even a minute. To avoid waiting, it is best when the balance is nearly reached to keep the battery key closed while changing R.

Having obtained a balance, try to determine approximately the time required for the current in the field to become steady, by closing the galvanometer key at different intervals after closing the battery key.

Report. — Report to contain all measurements of resistances.

Experiment 6. — (a) Preliminary Work with a Dynamo. (b) Operation of a Shunt Dynamo.

The purpose of this experiment is to acquaint the novice with the component parts of the dynamo and to familiarize him with their construction. It also calls attention to any defects which may exist.

The specific points to be noted under the head of defects are as follows:

(*a*) Whether or not there is sufficient oil in the bearings or cups.

(*b*) Condition of the brushes and commutator: the brushes should be put in proper condition if they are badly worn or incorrectly set, and if necessary, the commutator should be smoothed off with fine sand paper (not emery).

(*c*) Tension of springs on brush holders, these being given proper amount of tension.

(*d*) Ease of turning of armature, this being ascertained by rotating it with the hand, in the case of small machines, or by a lever in the case of large ones.

(*e*) Correctness of the connections for the particular type under investigation.

Some of the causes which prevent a dynamo from "building up" its field magnetism or exciting its field are added in order that if any of these troubles are met with, they can be recognized and remedied.

If a dynamo fails to "excite," it may be due to one or more of the following causes:

(*A*) Residual magnetism is weak or not present.

(*B*) Reversed field connections, causing whatever E.M.F. is generated to send current the wrong way through the field coils and thus weaken the residual magnetism instead of strengthening it.

(*C*) Short circuit, either in the machine or in the external circuit.

(*D*) Field coils opposed to each other, each tending to "build up" the field in the opposite direction.

(*E*) Open circuit in field coils or connections.

(*F*) The brushes may not be in the proper position on the commutator.

(*G*) Rheostat in the field circuit of too great resistance, thereby preventing sufficient current from passing through the field coils.

Report. — The points to be observed are those noted in the following table. Report on the general condition of the machine as indicated in *a*, *b*, *c*, etc.:

Type of Dynamo.

Shunt....................................
Series....................................
Compound..................................

Type of Armature.

Siemens drum ....
Gramme ring ....
Drum wound ring...........................
No. of sections ....
Conductors per section ....
Total No. of conductors...............

Armature.

E.M.F......................................
Current ....
Watts output..............................
Active length ....
Circumference in ft......................
Speed, R.P.M...............................
Peripheral speed in ft. per min......

Commutator.

Active length ....
Total length ....
Circumference in ft.......................
Peripheral speed in ft. per min......
Total no. of bars........................
No. of bars between brushes of opposite polarity.........................
Voltage between bars...................
Width of bars.............................
Width of insulation......................
Kind of brushes..........................
Brush area per set......................
Current density in brushes...........

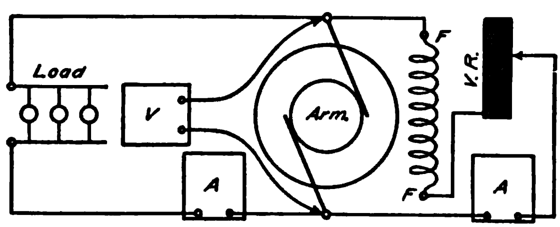
Field.

Shunt......................................
Series......................................
Compound.................................
No. of coils...............................
Method of winding.......................
No. of poles...............................
Pole pitch.................................
Pole width.................................
Pole length................................
Width of pole shoe ....
Length of pole shoe.....................

(b) Operation of a Shunt Dynamo.

A shunt dynamo is one whose field coils derive their exciting current from the armature of the machine. The coils are con-

Fig. 7.



nected directly across the armature terminals, thereby shunting part of the armature current from the external circuit. This will

be noticed from a study of Fig. 7, which shows the connections of a shunt wound dynamo.

The resistance of the field circuit is made large, as compared with the armature resistance, in order that only a small percentage of the current output of the machine may be used in this part of the dynamo. This is a constant loss and every endeavor is made to reduce it to a minimum. The armature of a dynamo is made of low resistance in order that the loss in it may be small, and also that the regulation of the E.M.F., with variations in load, may be satisfactory. A high field resistance also tends to provide good regulation, as the changes in the current, with change in load, are small. These slight changes in current do not materially affect the E.M.F. of the armature.

In a shunt dynamo where the external current changes, due to variation in the number of lamps, or the operation of motors or other devices the E.M.F. of the machine alters, if no regulation is effected by means of the rheostat placed in the field circuit. As the load increases, the "drop" in the armature increases, causing a decrease in E.M.F. at the armature and field terminals. The net result is that the E.M.F. falls, due to internal armature drop and decrease in magnetic flux due to decreased field current. This action will continue with increase in load until the dynamo's E.M.F. reaches zero. In order to overcome this action, the rheostat in the field circuit may be so changed as to decrease the resistance of this circuit and permit more current to pass around the field coils. This increases the flux and causes the E.M.F. to rise.

The opposite sequence of actions takes place where the external resistance increases. The E.M.F. increases and resistance has to be inserted in the field circuit to prevent the E.M.F. from rising too far.

A shunt dynamo will usually build up its own E.M.F. to the proper value, the action being started by the small E.M.F. due to residual magnetism in the field cores. This E.M.F. acts to send current through the coils, thus increasing the flux and caus-

ing the E.M.F. to increase. This action will continue until the iron has reached the point of saturation.

Method.— Before operating a dynamo, make the following determinations, the resistances being those at the room temperature :

1. Resistance of the field coils, using a Wheatstone bridge.

2. The resistance of the armature circuit and its parts by fall of potential, using sufficient current to give a large deflection on the instruments.

3. When these have been satisfactorily made, the machine can be run as a dynamo, and a load, such as lamps or any other convenient translating device connected to the machine. Before starting the dynamo, make the connections as shown in Fig. 7, inserting an ammeter of proper capacity in the external circuit as well as one in the field circuit, and place a voltmeter across the *terminals* of the machine.

4. In starting, the precaution must be taken to have the maximum resistance of the rheostat in series with the field coils, otherwise the machine may build up too rapidly and possibly to too high a voltage, thus burning out or otherwise endangering the lamps and apparatus connected to the terminals of the dynamo. In order to increase the E.M.F. of the machine the field resistance is gradually *decreased* until the potential of the machine has attained its proper value. When this condition has been reached, there should still be left in the rheostat some resistance which will allow for regulation of the E.M.F. when the load on the machine is increased and the E.M.F. tends to fall.

5. When the voltmeter indicates that the potential is at the proper value for the particular dynamo under test, connect a portion of the load, gradually increasing it until full load is attained. Note and record the effect of this action on the E.M.F. at the terminals. *Explain* this result and ascertain the method of *compensating* for it.

6. With dynamo running at constant speed and steady load, shift the brushes a short distance around the commutator by means of the rocker arm handle. *Note and explain the results.*

7. Temperature run. Measure the surface temperature of the armature, commutator, each bearing and field spool by placing a thermometer upon each part covered by a small piece of clean waste. Do not hold on with the hand as correct results can not be obtained. Fully load the dynamo at its rated E.M.F. and take all readings including temperatures of bearings and fields at ten minute intervals until the current in field coils becomes steady. On reaching this point, it will be known that the machine has arrived at its maximum temperature with full load. Shut down the machine first having made all arrangements to quickly measure the resistance of the armature circuit. Place thermometers on armature, commutator and pole tips as before and determine rise in temperature of parts.

Plot curves showing rise of temperature of various parts using time as abscissa. By the change in resistance determine the average temperature of the armature and field coils. (See Ex. 3.)

From the values of the currents, radiating surfaces and hot resistances, determine the watts per square inch radiated by the armature and fields.

Report to contain all observations, explanations and results called for above.

Experiment 7. — Characteristic Curves of a Shunt Dynamo.

The name "characteristic" was given by M. Marcel Deprez in 1881 to curves which Dr. Hopkinson used to represent the relations between the different properties of a dynamo. Since that time these have been extensively employed to illustrate graphically the interrelation of the variable factors of electrical machinery and appliances. Their use is most important, as it becomes possible to present a graphic representation of the variations which occur. As an aid in designing they are particularly useful, as their forms afford definite information as to the successful outcome of the calculations.

The characteristic curves which are to be determined and plotted, are indicated in Table V. the quantities to be observed for each curve being clearly shown therein.

TABLE V.

CHARACTERISTIC CURVES, SHUNT DYNAMO.

	1 Magnetization Curve.	2 Internal Characteristic.	3 External Characteristic.	4 Total Characteristic.	5 Armature Characteristic.	6 Armature Reaction.
Field current	Measure	Measure			Measure	Constant
External current			Measure		Measure	Measure
Total current				Calculate		
E.M.F. at terminals	Measure	Measure	Measure		Measure constant	Measure
E.M.F. in armature				Calculate		
External resistance	Open circuit	Open circuit	Variable	Variable	Variable	Variable
Field circuit resistance	Variable	Variable	Constant	Constant	Variable	Constant
How excited	Separately	Self	Self	Self	Self	Separately
Speed	Constant	Constant	Constant	Constant	Constant	Constant
TO PLOT CURVE USE FOR						
Abscissa	Field current	Field current	External current	Total current	External current	External current
Ordinate	E.M.F. at terminals	E.M.F. at terminals	E.M.F. at terminals	E.M.F. in armature	Field current	E.M.F. at terminals, and calculated drops

Experiment 7.—Part 1—Determination of the Magnetization or Saturation Curve of a Shunt Dynamo.

The *magnetization* or *saturation* curve of a dynamo shows the magnetic condition of the magnetic circuits as a whole from zero to full magnetization. The magnetization is produced by the ampère-turns of the field windings, these being the product of the number of turns in the field coils and the current in them. This magneto-motive force acting over the reluctance of the magnetic paths produces a magnetic flux. The E.M.F. of a dynamo is generated by continuously varying this flux through the armature coils, by rotating the coils with respect to the flux. The materials used in magnetic circuits possess the physical property of becoming magnetically saturated; that is, when the density of the flux becomes so great that it is difficult to increase it without greatly increasing the M.M.F. the material is said to have reached saturation. If this were not so, the magnetic flux might go on increasing directly with the M.M.F. While the primary purpose of the saturation curve is to indicate the magnetic condition of the magnetic paths as a

whole, there will also be shown that part of the curve upon which the machine should be operated to give the best regulation of E.M.F.

The M.M.F. $= 4\pi/10\, At$ and as $4\pi/10\, t$ is a constant, the M.M.F. can be expressed by the value of the current in the field coils.

The E.M.F. of a dynamo armature $= 2\Phi Nnp/(60 \times 10^8)\,c$ and as all but the flux Φ is a constant, with a constant speed, the E.M.F. is a measure of the flux values.

Therefore the magnetization curve can be expressed between the corresponding values of the field current and the E.M.F.'s at the armature terminals.

Method. — 1. The armature of the machine under test should be run at its rated speed, which should be recorded; currents,

TABLE VI.

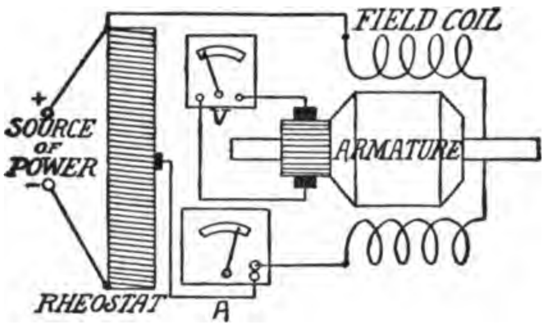
Magnetization Curve					
Going Up			Coming Down.		
Volts.	Field Current	Speed	Volts.	Field Current	Speed.

obtained from a suitable source of power, and ranging in value from zero to the full rated capacity of the field current should be passed through the field coils and the corresponding armature E.M.F.'s recorded. Table VI. shows the observations to be made. If there should be any variation in speed during the test a proportional correction of the E.M.F. should be made. As the field currents in field circuits are usually small, a low reading ammeter is essential. In order to vary the current through the wide limits required, it is necessary to employ a high variable resistance in series with the field, possessing a sufficient number of steps to give small variations in the current values. This pre-

supposes that the field is excited from some source of power of nearly the same E.M.F. as the machine under test. A high variable resistance is not always available and to avoid its use a second method is given, as follows:

2. Between an E.M.F. of the about the same value as that of the machine under test, place a resistance, such as a long length of iron or German silver wire or a rheostat with many points.

Fig. 8.



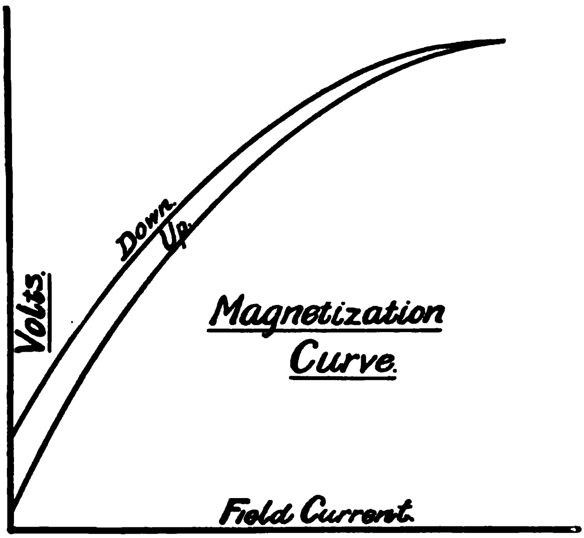
Between one end of this resistance and a contact brush movable along the wire, differences of potential will exist when current is passed through the wire. These can be applied to the shunt field of the dynamo by connecting one end of the resistance and the contact brush to the windings, as shown in Fig. 8, which further shows all the connections for this test. By using this method very accurate adjustments of the field current can be effected.

In determining the magnetization curve, always bring the magnetizing current *up to* the value at which it is desired to read; do not carry it above this point and then reduce it. The reason for this is that a higher point is obtained on the curve if the current is brought *down* to the proper reading than when it is brought *up* to the same value.

The higher point is that one which would be obtained on what is known as the descending magnetization curve, this being found by reducing the field currents from the full value attained. The two curves will be slightly separated owing to *hysteresis* or the magnetic retentiveness of the materials, the descending curve giving the higher values for E.M.F.'s with equal M.M.F.'s.

Report. — A curve sheet as in Fig. 9, tabulated results and conclusions.

Fig. 9.



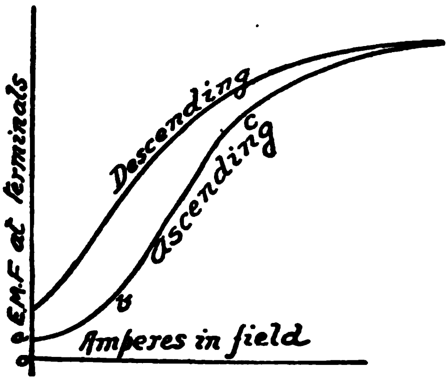
Experiment 7. — Part 2 — Determination of the Internal Characteristic or "Building up" Curve of a Shunt Dynamo.

This curve shows the relation which exists between the M.M.F. or *At* of the field windings and the flux through the armature, the armature exciting its own field, thus operating as a self-excited dynamo. The values are expressed as in the magnetization curve.

The curve illustrated in Fig. 10 shows the manner in which a shunt dynamo builds up its E.M.F. At any constant speed the resistance of the field circuit must be reduced to a value where the E.M.F. as at *a*, due to residual magnetism in the fields, will send sufficient current through the field circuit to increase the flux and E.M.F. When this increase commences, as at *b*, Fig. 10, the rise in E.M.F. takes place rapidly and without any further change in the resistance of the field circuit. The machine is operating as a series dynamo and has the same characteristics as that type of machine. The E.M.F. will increase until the mag-

netic circuit has become well saturated, as at *c*. No increase in M.M.F. can now occur without decreasing the field resistance, and consequently the E.M.F. remains stationary. The field rheostat can now be varied, thus altering the current and raising

Fig. 10.

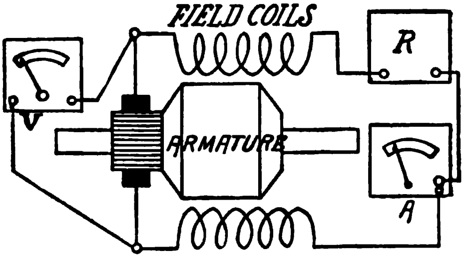


the E.M.F. The curve will incline towards the axis of x, showing that the iron of the circuit is becoming rapidly saturated.

Method. — Connect the machine to be tested, as shown in Fig. 11. and record the simultaneous values of the field current and E.M.F.'s for increasing and decreasing values of the field currents. The difference shown by the curves in Fig. 10 is due, as in the magnetization curve, to hysteresis or magnetic lag.

Report. — Present all results tabulated and a curve showing the relation between field ampères and armature volts. Full explanation of action of machine.

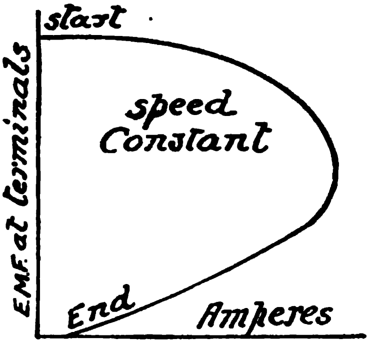
Fig. 11.



Experiment 7.—Part 3—Determination of the External Characteristic or "Working" Curve of a Shunt Dynamo.

The *external characteristic* or "working" curve of a shunt dynamo shows the effect of the increase of armature current upon

Fig. 12.



the terminal E.M.F., where no attempt is made to regulate the potential of the machine. It is a measure of the inherent regulation of the machine for constant potential. If the armature resistance is large the regulation will be poor and *vice versa.*

If a shunt dynamo be self excited to its rated E.M.F. and the current through its armature gradually increased by adding lamps or otherwise increasing the external conductance, the E.M.F. at the armature *terminals* would gradually decrease, due to *IR* loss in armature, armature reaction and decrease in field current. When the field current becomes so decreased that any further small decrease widely changes the E.M.F., both this and the current rapidly decrease, eventually falling to nearly zero, and taking the form shown in Fig. 12. In the event of a shunt dynamo being short-circuited, this action takes place but accompanied by violent sparking and mechanical strain.

The curve does not pass through zero due to the voltage caused by residual magnetism. The terminal voltage becomes zero or nearly so because all of the generated voltage due to residual magnetism is being expended over the armature circuit.

Method. — Operate the machine as a shunt dynamo with con-

nections as shown in Fig. 7 placing a low reading ammeter in the field circuit. The sum of this current and that in the external circuit will be the total current delivered by the armature. The speed should be constant. Readings should be taken of the external and field currents, E.M.F. at terminals and speed as shown

TABLE VII.

E.M.F.	External Current.	Shunt Field Current.	Speed.

in Table VII. The machine should be brought up to its rated E.M.F. and then the field resistance left fixed.

External currents should then be increased until the machine fails to generate. The result will be similar to the curve in Fig. 12.

Report. — All results in tabular form, curve showing graphical results, description of the operation of the machine and explanation of all phenomena noted.

Experiment 7. — Part 4 — The Total Characteristic of a Shunt Dynamo.

This shows the relation between the total current and the total E.M.F. of the armature.

Method. — The total current is the sum of the external and field currents $I + I_{sh}$, while the total E.M.F $= e + (I + I_{sh})R$.

$e =$ terminal E.M.F.

$R =$ resistance of armature.

To the corresponding values of the previous curve add these increments, thus obtaining another curve which will be the total characteristic. This is to be plotted on the same sheet as the external characteristic.

Report. — Curve showing results in graphic form. Present conclusions.

Experiment 7. — Part 5 — The Armature Characteristic of a Shunt Dynamo.

The armature characteristic expresses the relation between the external and field currents, the E.M.F. at the terminals being kept constant and the armature running at a constant speed. A curve plotted from these readings will show the increase in the field ampère-turns necessary to compensate for the drop of potential due to the increased external current. The total change in the ampère-turns divided by the maximum ampère-turns employed will give the percentage increase under any condition of load.

This method gives the value of the ampère-turns to change a shunt into a compound dynamo.

Dividing the maximum increase of ampère-turns by the external current gives the actual number of turns necessary for the series field winding.

Method. — Make connections as in Part 3 and take simultaneous readings in about 10 steps, of external and field currents, keeping E.M.F. constant at the terminals. Speed is to be recorded. Record values as in Table VII.

Report. — Plot results in a curve and determine the per cent. increase in ampère-turns from no load to full-load.

All observations tabulated. Conclusions.

Experiment 7. — Part 6 — Determination of the Armature Reaction in a Shunt Dynamo.

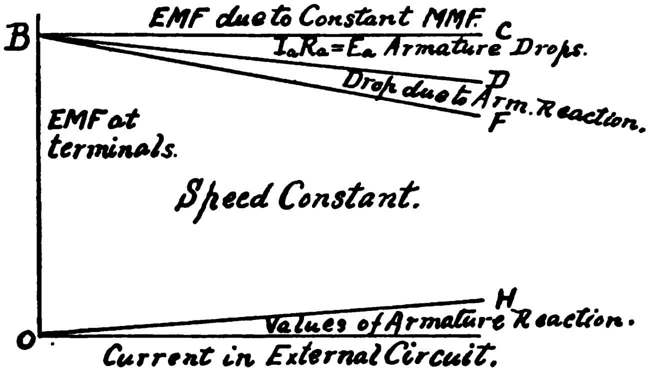
In every dynamo and motor the ampère-turns of the armature generate a flux which acts on the flux generated by the field winding so as to produce a distortion as well as a neutralization of a portion of the latter. This effect is known as armature reaction. Let us suppose a separately excited dynamo giving a certain E.M.F. at no load. When load is added the E.M.F. decreases and if it were not for armature reaction this decrease would be proportional to the current increase. It is found that

the difference is sometimes quite considerable indicating a large armature reaction. In order to determine its amount proceed as follows:

Method. — The field is to be separately excited until the armature has attained its proper potential at its rated speed. The field current is left constant throughout the test. Load is now applied to the armature and simultaneous readings taken of the current, E.M.F. and speed.

The readings are to be plotted as in Fig. 13.

Fig. 13.



BC shows E.M.F. given by constant M.M.F.

BD is the line which is derived by subtracting armature drops from *BC*.

BF is the curve which represents the observed values of the E.M.F. The difference between the ordinates of *BD* and *BF* are the values of the armature reaction. These values are to be plotted at the base of the sheet, as shown in *OH*, in order that they may be read directly. The equation for these values is

$$\text{armature reaction values} = E - (e + I_aR_a).$$

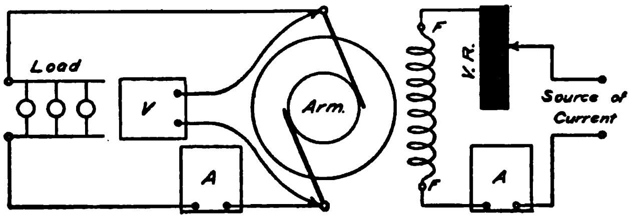
The connections are shown in Fig. 14.

Report. — All results and conclusions. Curve sheet giving graphic representation. Percentage that armature reaction bears to both armature drop and total decrease in E.M.F. at full load.

Experiment 8. — Characteristic Curves of a Series Dynamo.

A series dynamo is one wherein the armature, field coils and the external circuit are in series. At any part of the circuit the

Fig. 14.

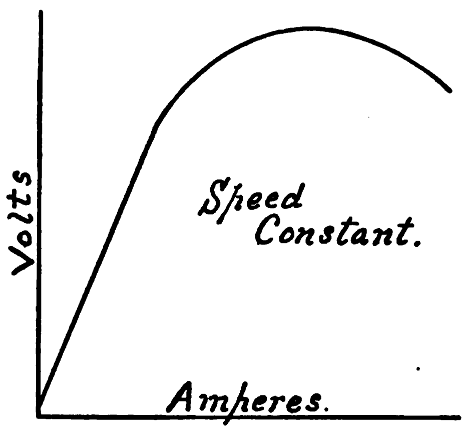


current has the same value as at any other part. The use of this type of machine is limited, as in its simple form both E.M.F. and current vary with any change in either. When a special regulating device is used, the machine is employed in arc lighting to provide a constant current and varying potential.

The purpose of the following tests is to show the relation between the variable quantities in a plain series dynamo, when the speed remains constant.

When a series dynamo is run with the external circuit open, it will generate no potential, except that due to residual magnetism,

Fig. 15.



as there will be no current passing through the field. But if the circuit be closed and its resistance reduced to a proper value, the armature will commence to generate an E.M.F. which will send more current through the circuit. The E.M.F. and current will further increase, and this action will continue until the internal losses due to armature reaction and drop prevent the E.M.F. from increasing. The curve expressing this action will take the form shown in Fig. 15.

The characteristic curves which are to be obtained and plotted are as follows, the table giving the quantities which are to be observed for each curve.

TABLE VIII.

CHARACTERISTIC CURVES, SERIES DYNAMO.

	1 Magnetization Curve.	2 External Characteristic.	3 Total Characteristic.
Field Current	Measure	Same as External	
External Current		Measure	
E.M.F. at terminals		Measure	
E.M.F. in armature	Measure		Calculate
External Resistance	Open Circuit	Variable	
How excited	Separately	Self	
Speed	Constant	Constant	Constant
TO PLOT CURVE USE FOR			
Abscissas	Field Current	Current	Current
Ordinates	E.M.F.	E.M.F. at terminals	E.M.F. in armature

In any particular machine at a given speed there is a definite value of the external resistance at which the machine will generate. This is known as the "critical resistance" for this speed.

Experiment 8. — Part 1 — Magnetization Curve of a Series Dynamo.

The magnetization curve, as in a shunt dynamo (Experiment 7, Part I), shows the relation between the number of lines of force in the armature and the magnetomotive force, the speed being constant.

Method. — The method to be followed is shown in Experiment 7, the connections being similar to Fig. 8.

Report. — Curves showing results. Conclusions as to condition of magnetic circuit.

Experiment 8. — Part 2 — External Characteristic of a Series Dynamo.

The external characteristic shows the relation between the current and terminal E.M.F., the armature rotating at a constant speed.

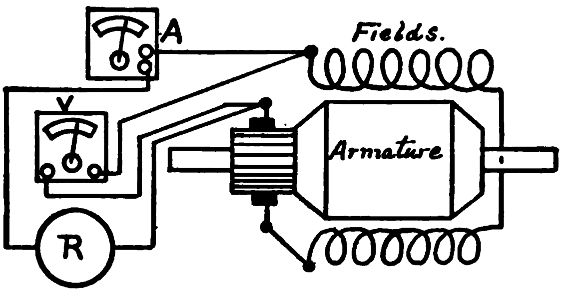
This curve is the operating characteristic of the machine.

When the external resistance has been reduced to the proper value for the speed, the E.M.F. will commence to increase and will continue as indicated in Experiment 7, Part 2.

Method. — Make connections as shown in Fig. 16, placing a quick-break switch in the circuit.

Adjust the speed to the proper value and then vary the external resistance until the E.M.F. commences to increase slowly. Determine the value of the external resistance at which the ma-

Fig. 16.



chine commences to build up. This is found from the current and E.M.F. recorded at that point. Take simultaneous readings of the E.M.F. and current from no load to full load and then in the reverse direction.

Report. — Curves showing results. Value of "critical resistance" at rated speed. Conclusions deduced from results.

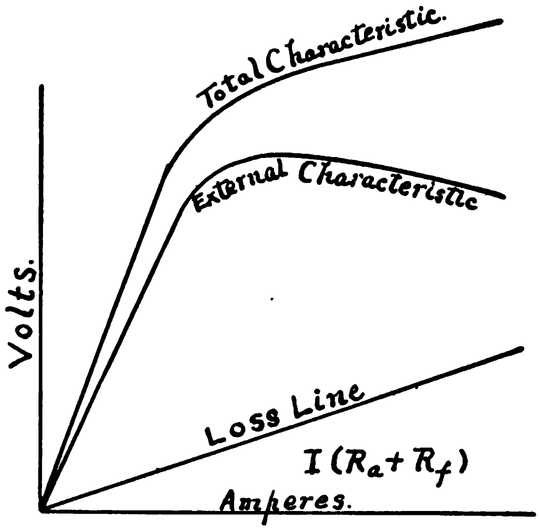
Experiment 8. — Part 3 — Total Characteristic of a Series Dynamo.

The total characteristic expresses the relation between the

current and total E.M.F. generated. It is found by calculating the internal drops corresponding to the values of the current and adding them to the corresponding points of the external characteristic curve.

Method. — Determine the resistance of the fields and armature of the dynamo and with the values of the current used in Part 2 calculate the drops. Add these to the external characteristic curve thus giving the total E.M.F. generated. Plot the values of these drops as shown in Fig. 17. The lower curve is known as the loss line, the tangent of the angle being equal to the resistance of the field and armature.

Fig. 17.



Report. — Curves as shown. Any conclusions derived from results.

Experiment 9. — Operation of a Compound Dynamo.

In the case of a shunt dynamo, the variation of the power delivered to the external circuits will cause the E.M.F. at the terminals of the machine to vary, unless the current in the shunt field windings is altered in accordance with the variation in power

delivered. It is quite impracticable to do this when the power is rapidly fluctuating through wide limits, first, because it would necessitate constant attendance at the regulating devices of the various machines, and, secondly, the variations could not be compensated for quickly enough to maintain the E.M.F. constant. This necessary regulation can be accomplished automatically and without the employment of mechanical apparatus by dividing the windings of the fields into two circuits, one known as the shunt winding, similar to that of the plain shunt dynamo, the other known as the series winding, of large wire and low resistance. The latter usually carries all of the total current output of the machine, as it is in series with the armature and external circuit. The shunt winding gives the correct no-load E.M.F. of the dynamo, while the series coil, with either the whole or part of the external current traversing it, increases the flux through the armature. This compensates for the loss of E.M.F. due to the armature reaction and drop and the drop in the series field coils. If the number of series ampère-turns is large enough, the increased flux can be made more than sufficient to compensate for all the internal losses of E.M.F., and the external E.M.F. will consequently rise with increase of current in the external circuit. In lighting systems and in isolated plants the over-compounding, as it is called, is about 2 or 3 per cent. In railway work the dynamos are usually over-compounded for 10 per cent., the E.M.F. rising from 500 volts at no load to 550 at full load. This regulation is entirely automatic and almost instantaneous. The amount of the compounding can be altered by placing across the ends of the series windings an iron or German silver shunt, which diverts part of the current from the series winding and prevents the E.M.F. from rising to as high a value as it would with the total current traversing the coils. By removing this shunt the full effect of the series ampère-turns can be made available.

Care must be exercised in the operation of a compound dynamo or of such dynamos in parallel, for if a machine is sub-

jected to a considerable overload or to a short circuit, the E.M.F. and current will increase, and great strains will be produced in the machine and driving mechanisms. In the case of belted dynamos, the belt may fly off, causing damage to property and life. Severe sparking occurs at the brushes and commutator, leading to injury of the machine. This action is quite in contrast with that of the shunt dynamo, whose potential decreases with increase of load. The short-circuiting of a shunt dynamo reduces its E.M.F. and current to zero.

Method. — Operation of the machine.

The following measurements are first to be made:

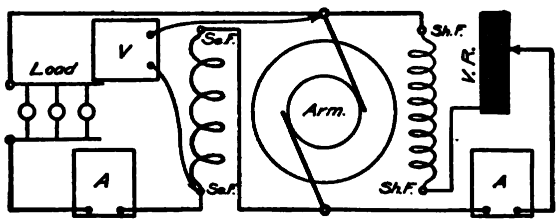
1. Resistance of shunt field coils, by fall of potential or Wheatstone Bridge.

2. Resistance of the total armature circuit, by fall of potential method.

3. Resistance of series field coils, by fall of potential. The connections for a compound dynamo are shown in general form in Fig. 18.

Observe the instructions given in Experiment 6 (*a*) before starting the machine.

Fig. 18.



4. It is very important that a compound dynamo should be operated at its rated speed, otherwise the proper compounding effect is not obtained. See that the speed is right for the machine under test and then build up the E.M.F. to the correct no-load value, by varying the resistance in the shunt field circuit. The external circuit can then be closed and a small load applied to the machine. The brushes can be adjusted to that point where there is the minimum sparking. When the load is applied, the E.M.F.

should be observed, in order to ascertain if the series ampère-turns are increasing the E.M.F. or decreasing it. In the latter event, the turns are acting against the shunt winding and the direction of the current through the former should be reversed.

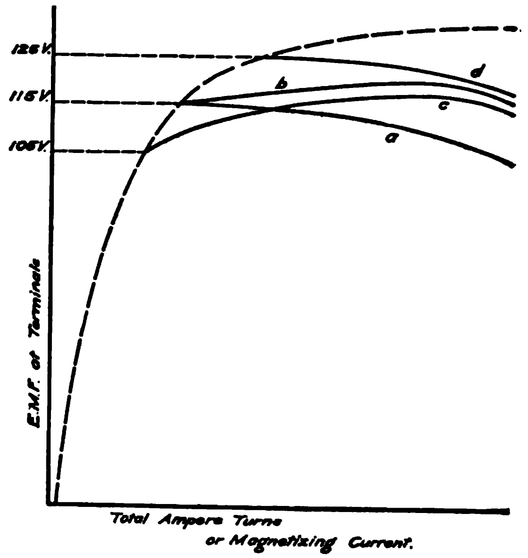
The load can now be varied and its effect upon the E.M.F. noted.

The *compound characteristic* or "working" curve gives the relation which exists between the corresponding values of the terminal E.M.F.'s and the total current in the external circuit, the machine operating always at its *rated speed.*

The curve which can be plotted from these values illustrates the compounding which exists at the rated speed. If the machine is designed to maintain a constant E.M.F. at the terminals, the curve will be a straight line, using current values for abscissas and terminal volts for ordinates. If the machine is over-compounded the curve will gradually rise with increase in load.

Method. — The E.M.F. of the machine is adjusted to its proper value at no load, the load gradually increased and corresponding values of the terminal E.M.F. and external current are read.

Fig. 19.



Keep speed constant.

The forms of the curves are shown in Fig. 19. Those for cases (*e*) and (*f*) are omitted for simplicity but would be similar to (*c*) and (*d*) respectively.

Ampere-turns are used as abscissæ since it is evident that the compounding effect obtained depends upon the no load flux density in the magnetic circuit, which depends upon the relative magnitude of the shunt ampere-turns. The total magnetizing current may be used as abscissæ if the value of the turns on the shunt and series fields are not known. The total magnetizing current is equal to the shunt field current plus the current in the series winding expressed in terms of the shunt field current. This may be called the equivalent shunt field current and is determined as follows:

$$\text{Equivalent Shunt Current} = \text{Series Field Current} \times \frac{\text{Series Turns}}{\text{Shunt Turns}}.$$

The ratio between series turns and shunt turns is found by running dynamo at rated speed with armature on open circuit and separately exciting shunt field to give a certain terminal voltage (series fields on open circuit), then separately excite series field passing sufficient current through it to produce same terminal voltage as before. Shunt field must be on open circuit. Since voltage and speed are same in both instances the ampere turns must be the same, hence Series Current × Series Turns = Shunt Current × Shunt Turns or

$$\frac{\text{Series Turns}}{\text{Shunt Turns}} = \frac{\text{Shunt Current}}{\text{Series Current}}.$$

Since the currents are known the ratio between the turns may be calculated.

If the series field is shunted it will be necessary to insert an ammeter in the series field in order to determine the series current during this experiment. The curves obtained by plotting against ampere-turns or total magnetizing current as explained will be similar in form to the external characteristic since the series field

current is proportional to the external current. The broken line in Fig. 19 shows the magnetization curve of the dynamo. This is determined as explained in experiment 10, part 1.

Make six sets of readings as follows and tabulate as in Table IX.

TABLE IX.

A	B	C	D	E	F	G
Terminal E.M.F.	External Current	Series Field Current	Shunt Cur. Equivalent To Series Field Cur.	Shunt Field Current	Total Magnetizing Current	Speed
			C × K		D + E	

$$K = \frac{\text{Series Turns}}{\text{Shunt Turns}}.$$

(*a*) Start at proper no-load E.M.F. and speed, and permit speed and E.M.F. to vary while load is increased.

(*b*) Start as before but keep speed constant for every increase in load.

(*c*) Start at an E.M.F. 15 per cent. lower than that at which the machine is rated, speed constant throughout test and increase load as before.

(*d*) Start at an E.M.F. 15 per cent. higher than that at which the machine is rated, speed constant throughout test and increase load as before.

(*e*) Start at proper no-load E.M.F., speed 15 per cent. above rated value, speed constant throughout test and increase load as before.

(*f*) Start at proper no-load E.M.F., speed 15 per cent. below rated value, speed constant throughout test and increase load as before.

Report. — Plot curves on one sheet from tabulated results and draw conclusions from them. Explain fully.

Experiment 10.—Characteristic Curves of a Compound Dynamo.

In Experiment 9 is given a description of the action and operation of a compound dynamo, to which reference should be made for information on this subject.

The characteristic curves which are to be obtained and the quantities which are to be observed for each curve, are shown in the table following.

TABLE X.

	1 Magnetization Curve.	2 Compound Characteristic.	3 Total Characteristic.	4 Armature Reaction
Shunt field current	Measure variable	Measure		Constant
External current		Measure		Variable
Total current			$I + I_{sh}$ calculate	
E.M.F. at terminals		Measure		
E.M.F. of armature	Measure		Calculate	Measure
External resistance	Open circuit	Variable		Variable
Shunt field resistance	Variable	Constant		Constant
How excited	Shunt and series separately	Self		Shunt separately
Speed	Constant	Constant	Constant	Constant

TO PLOT CURVE USE FOR

Abscissa	Field current or ampère-turns on field	I External current	$I + I_{sh} = I_t$ Total current	External current
Ordinate	E.M.F. of armature	E.M.F. at terminals	E.M.F. in armature	E.M.F. at brushes

Experiment 10. — Part 1 — Magnetization Curve.

In a compound dynamo the first portion of the magnetization curve up to the no load E.M.F. is produced by the ampère-turns of the shunt field windings, the relation being similar to the corresponding curve of a shunt dyamo and the variables being expressed by the E.M.F. of the armature and the ampère-turns of the field. With the ampère-turns of the shunt field remaining fixed at the value which gives the no load E.M.F., the balance

of the curve is produced by the ampère-turns of the line current through the series field coils. These series ampère-turns, if acting on the magnetic circuits in the same direction as the shunt-turns, will increase the flux and raise the E.M.F. of the armature. If acting oppositely, the E.M.F. will decrease.

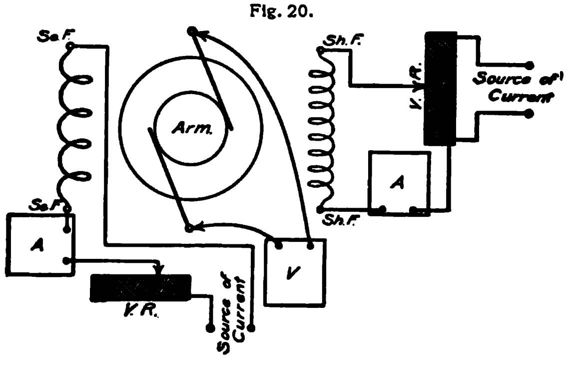
Method. — Separately excite the shunt field by methods cited in Experiment 7, Part 1.

Separately excite the series field, placing in circuit an ammeter and a rheostat. Bring the E.M.F. of the armature up to no load value by means of the shunt field, taking readings as in similar shunt characteristics. With the last value of the shunt current remaining fixed, further excite the magnetic circuit by introducing current in the series coils, taking readings of this current and E.M.F. at armature.

When the current has reached the full load value for the machine, it is to be decreased in the same steps as when increased and, after reaching zero, the shunt current is to be reduced in a similar manner..

The connections for this test are given in Fig. 20.

Fig. 20.



If the number of turns in the field windings is not known it is necessary to determine the ratio between the turns of the series and shunt in order that the curve may be plotted to the proper scale. This ratio can be ascertained as explained in Experiment 9.

Report. — Present curves showing relation between field currents or ampere-turns and E.M.F.'s. Discuss curves obtained.

Experiment 10. — Part 2 — Compound or External Characteristic.

This curve shows the relation between the E.M.F.'s at the terminals of the machine and the external current, the speed being constant and at its rated value.

The field windings of a compound dynamo may be so adjusted as to keep a constant potential at the terminals from no load to full load, or it may produce a uniform increase in potential which is technically known as "over-compounding." The latter construction provides a means for keeping the potential constant at some distant point on the line, the difference between the no load and full load potential representing the loss in the line.

There are two distinct arrangements of the connections in a compound dynamo, known respectively as the long shunt and the short shunt. In the former the shunt fields are connected across the two outside terminals, while in the latter the shunt winding is connected to the brushes and therefore inside of the series coils. The first arrangement provides a constant E.M.F. across the shunt fields when the machine is not over compounded, while in the second the E.M.F. across the shunt fields increases with increase of external load. As a result of the latter method, the shunt fields provide a slightly increased magnetization with increasing loads.

Method. — Make connections as shown in Fig. 18, using short shunt arrangement. The E.M.F. of the machine is to be adjusted to its value at no load, the load gradually increased and simultaneous values of the *terminal* E.M.F. and external current read. Making these respectively the ordinates and abscissas of a curve, the inherent regulation of the machine can be determined. The speed is to be observed carefully, so that if any change does occur, it can be recorded.

The forms of curves are shown in Fig. 19.

Report. — Curves showing regulation from no load to full load as in parts (*b*), (*c*) and (*d*) of Experiment 9. Obtain the data for these curves from Experiment 9 and draw curves on a separate sheet for this experiment. Discussion of curves.

Experiment 10. — Part 3 — Total Characteristic.

This curve expresses the relation between the total number of lines of force through the armature and the total armature current. The values for plotting the curve are obtained from the observed readings of the compound curve and the known resistances of the armature and series coils.

Method.— Ascertain the drop over the series coils due to the external current. This added to the terminal E.M.F. gives the E.M.F. at the brushes or armature terminals. Determine the drop in the armature due to the total current, which is the sum of the shunt field and external currents. Add these drops to the armature terminal E.M.F. thereby giving the E.M.F. generated in the armature. These points can be laid off from the compound curve, thereby showing the losses due to internal resistance.

For any value of the total current $(I + I_{sh})$, the E.M.F. in the armature will be:

$$E = E_{xt} + [(I_{ext}R_{sf}) + (I_{ext} + I_{sh})R_a]$$

Using total current values for abscissas and volts lost over internal resistance for ordinates, lay off curve at bottom of sheet. This will show the actual loss with any given current and can be read directly.

Report.— Curve on same sheet as compound characteristic. Ascertain per cent. of armature potential lost over internal resistances at full load. Discuss curves.

Experiment 10.— Part 4 — Armature reaction.

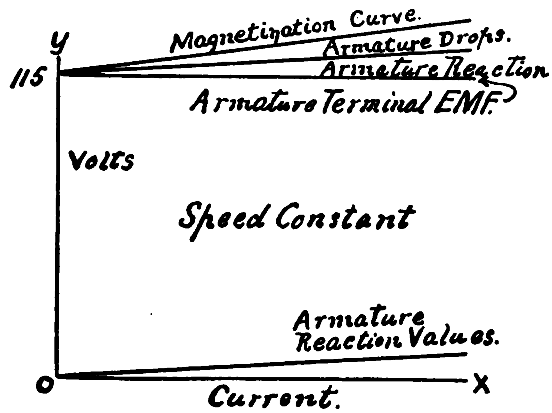
Armature reaction in a compound dynamo is not as apparent as in a shunt dynamo, for the reason that the ampère-turns of the series coils automatically compensate for the decrease in E.M.F. due to the flux produced by the armature ampère-turns reacting on the flux of the fields. It nevertheless is an important factor in determining the design of an armature to give constant E.M.F., and therefore there is given herewith a method for ascertaining the per cent. by which it reduces the armature E.M.F.

Generally with the brushes in a fixed position, giving a constant lead, armature reaction is a direct function of the current. Therefore in this work the brushes are to remain fixed.

Method.— Separately excite the shunt field so that the armature E.M.F. is the same as it was under no load conditions in the magnetization curve, also being careful that the speed is the same. The shunt current is to be kept constant throughout the balance of the work.

Then add load to the machine, using the series coils as is ordinarily done. This provides conditions which are similar to those when the machine is in service. Record the E.M.F. at the *armature terminals* besides the external current and speed for every change in the current.

Fig. 21.



Calculate the armature drop due to the different currents, and deduct these values from the points on the upper part of the magnetization curve corresponding to these currents. A curve drawn through these points will lie between the magnetization curve and the curve of constant potential, which is a straight line parallel to X. The difference between the latter and the calculated curve gives the E.M.F. loss due to armature reaction. Starting at the intersection of the coördinates, plot the armature

reaction values corresponding to the currents, thus giving the actual losses.

The general form of the results is shown in Fig. 21.

If the compounding curve were a straight line parallel to X, the value of the reactions could be derived directly from it without following the above procedure.

Report. — Curves as above. Percentage that armature reaction drop is of full load armature drop.

Experiment 11.— Difference of Potential Around the Commutator.*

This experiment is designed to illustrate the method of determining the E.M.F.'s generated by the armature coils of a dynamo in the different portions of the magnetic field.

In all closed coil armatures the sections are so connected that the E.M.F.'s generated in them are added, thereby giving the full difference of potential of the armature across the brushes. The E.M.F. of each section may be small, but enough sections are provided to give the E.M.F. desired. It is oftentimes desirable to investigate not only the E.M.F. generated in each section but also the distribution of the magnetic flux in the air gap of dynamos, the information thus obtained leading to the improved design of the fields and armatures.

The distribution of the magnetic flux across the pole face depends upon the design of the machine and also upon the value of the armature current, since the armature ampere-turns produce a flux which reacts upon the field flux distorting and deeasing it.

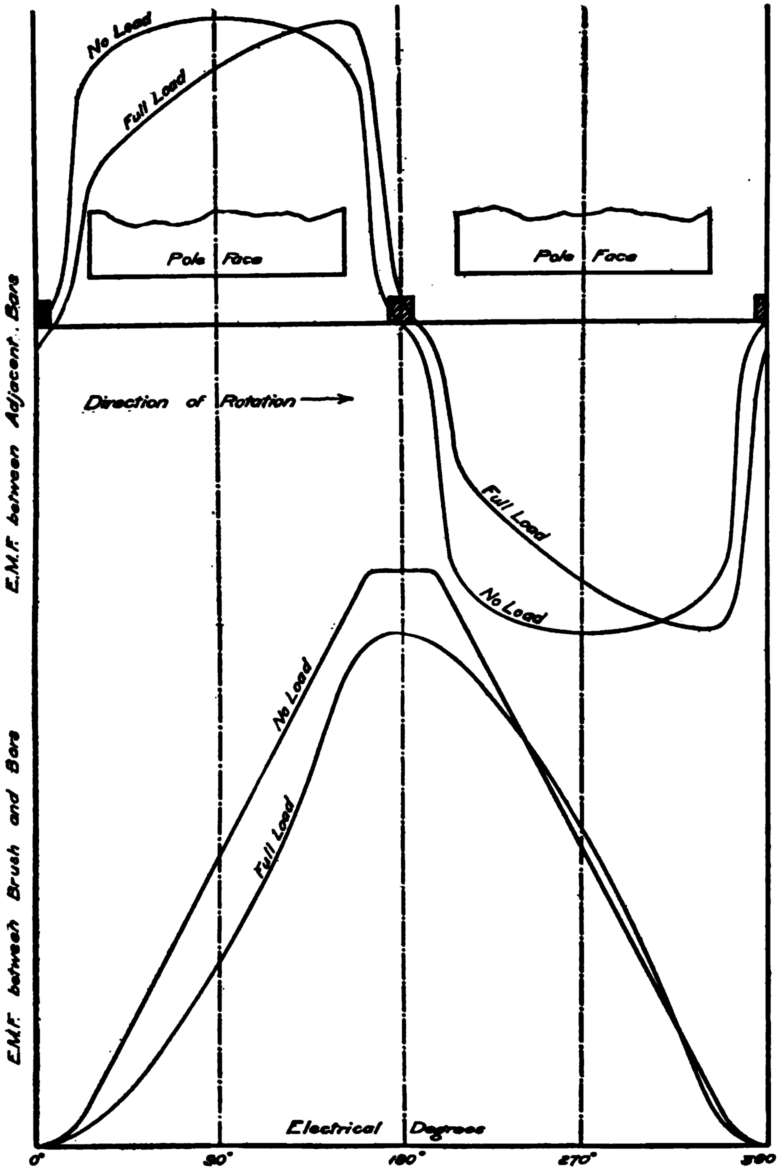
The distribution of the magnetic flux may be shown by revolving a coil through the field at a uniform velocity and measuring the E.M.F. generated in the coil for different angular positions in the magnetic field. For

$$E = \frac{2\Phi N n p}{60 \times 10^8 \times c} \quad \text{or } E = \Phi K$$

if the speed be held constant.

* Dynamo Electric Machinery, Thompson, Chapter IV.

Fig. 22.


No Load
Full Load
Pole Face
Pole Face
Direction of Rotation
Full Load
No Load
No Load
Full Load
E.M.F. between Adjacent Bars
E.M.F. between Brush and Bars
Electrical Degrees
0°
90°
180°
270°
360

The curves in Fig. 22 show the distribution of the magnetic flux in a shunt dynamo for no load and full load. The flux distribution is symmetrical at no load, while the effect of load is seen to cause a distortion of the flux in the direction of rotation, in the case of a dynamo, the opposite holding true for a motor.

The upper curves show the E.M.F.'s generated in a coil during one complete magnetic cycle, *i. e.*, in passing from a given point with respect to any pole to a like point with respect to the adjacent pole of the same sign. These curves show that the potentials generated in coils in different parts of the field are not equal. The lower curves show the rise in potential from one brush to the other by the method of adding the separate E.M.F.'s generated.

In order to investigate these phenomena a number of methods have been developed. Among these are the following:

1. Method of exploring brushes.
2. Mordey's Method.

Method 1.—Suitably attached to a dynamo are two exploring brushes, which can be moved around the commutator and fixed at intervals corresponding to the distance between the centers of the bars. The brushes are set apart a distance equal to the distance between the centers of the commutator sections. These brushes are connected to a voltmeter of suitable range and when the armature is operated in the excited field, E.M.F. readings in different parts of the field can be made by rotating the brushes about the commutator.

A set of readings, taken completely around the commutator, at both no load and full load with constant field current, is to be made; the results to be plotted as shown in Fig. 22 and to the same set of coördinates. Hold speed constant. Electrical degrees equal mechanical degrees times the number of pairs of poles on the machine. In a six pole machine it would be necessary to move a coil through only 120° of the circumference in order to obtain the complete curve of magnetic distribution as shown in Fig. 22.

Method 2. — This method employs only one brush and the voltmeter, the readings of the potential being taken between the exploring brush and one of the dynamo brushes. Use one of the brushes employed in Method 1, lifting the other from the commutator and connect a voltmeter of suitable range between the former and one of the dynamo brushes. Operate the armature under similar conditions as before taking two sets of readings, one at no load and one at full load. Plot both curves as shown in Fig. 22, and to the same set of coördinates. Hold speed constant.

Report. — Record all observations and present curves showing results. Indicate on the curve sheet the angular distance covered by the fields and interpolar space. Also direction of rotation. Present conclusions based on results obtained.

Experiment 12. — Operation of a Starting Box.

A starting box or motor starter is a protective device for limiting the rate at which energy is delivered to the armature of a motor on starting. When at rest, the *IR* drop is the only reaction in a motor armature, which can balance the impressed voltage. The resistance of a motor armature is always relatively small in order to minimize energy losses in this part of the circuit. Hence, if a motor be connected directly across the line on starting, a heavy inrush of current will occur.

The value of this current is $I_a = \frac{E_a}{R_a}$.

E_a = voltage impressed across the armature.

I_a = armature current.

R_a = armature resistance.

E_1 = line voltage.

Since R_a is small as compared to E_a, when E_a is equal to E_1, I_a is of abnormnal value, causing circuit breakers or fuses to blow, or if these protective devices be not employed, the armature winding may be burnt out.

In order to start a motor at no load, a certain torque is required. This torque developed by a motor is proportional to the

product of its field flux and armature current. With a given field flux the torque developed is proportional to the armature current. Hence on starting at no load, enough current must flow through the motor's armature to furnish sufficient assisting torque to overcome resistance or counter torque of motor due to friction, windage, hysteresis, and eddy currents. This starting current is limited in value and controlled by means of an adjustable resistance connected in series with the armature and having a current carrying capacity equal to or somewhat greater than that of the rated full load current of the motor in question. Motor starters are usually designed to carry one and a half times the rated full load current for one minute without injury. This adjustable resistance is called a "starting box" or "starter." Its total resistance R_b is such that when placed in series with the armature resistance across the line E.M.F. sufficient current flows through the armature to start the motor, which has its fields excited to their normal value. Under certain conditions of operation, a motor may take a current greater than its full load current on starting. This condition will exist when a motor is operating heavy shafting, etc., a large amount of energy being required to accelerate the dead weight of this shafting. The starting box must be designed to handle these large currents and at the same time permit a smooth acceleration.

As soon as the motor starts, an additional reaction is introduced, which acts to limit the flow of current. This reaction is the C.E.M.F. of the motor armature due to rotation of its inductors in the magnetic field. The armature current is now expressed by the equation

$$I_a = \frac{E_1 - e}{R_a + R_b}.$$

e = C.E.M.F. of motor.

R_b = starting box resistance.

As the resistance R_b is decreased, the motor speeds up until e increases sufficiently to cause I_a to assume that value demanded by the counter torque of the motor. The condition now obtain-

ing is that the fraction of the line voltage, which is being dropped across the armature is increasing, and as the speed of a motor is proportional to the armature's impressed voltage, the motor speed increases accordingly. When the adjustable resistance R_b is entirely cut out, full line voltage is impressed across the motor, which then runs at normal speed. Hence it is seen that if the armature voltage is gradually increased by cutting out an adjustable resistance in series with it, the flow of current through the armature is maintained at its normal value and the speed is brought to its normal value without an excessive inrush of current.

If a motor were thrown directly across the line and its armature inductors were of sufficient size to carry the current which would flow as determined by the equation

$$I_a = \frac{E_1}{R_a}$$

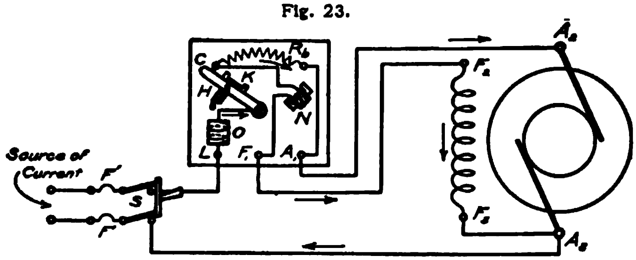
the motor would accelerate at a very high rate until normal speed was obtained. For this speed the current flowing would be given by the equation

$$I_a = \frac{E_1 - e}{R_a}.$$

This sudden application of voltage, however, results in abnormal conditions placing the motor under severe strain and should be avoided.

The sketch of a starting box and its auxiliary devices and description of the same follow.

Fig. 23.



R_b is the adjustable resistance in series with the armature of the motor.

C is the moving arm which cuts out R_b, when moved to the right.

Protective features of the Starting Box.

The three devices used in connection with a starting box to protect a motor are:

(1) Fuses, (2) Overload Release, (3) No Voltage Release.

If a motor be started under a heavy load or by cutting out the starting resistance too rapidly, a large current will flow through its armature. To prevent damage, the first two devices above mentioned are employed. Fuses ($F'F'$) having a capacity of about twice the rated full load current of the motor should be placed in each side of the supply line at the switch (S). The overload release (O) is a circuit breaker usually placed on the starting box. This should be set to blow at about 1.5 times the rated full load current of the motor. If excessive current be taken by the motor, the breaker will open before the fuses melt, as they have a certain time element which prevents them from acting instantly. Should the breaker fail to operate, the fuses furnish a further protection.

The no-voltage release is a device which automatically cuts a motor off the line should the line voltage diminish considerably or fall to zero. Should the line voltage fall to such an extent as to cause the motor to stop, the latter would constitute a short circuit across the line when the voltage resumed its normal value, unless the starting arm is brought to the off position. This function is performed by the spring (H) which acts against the magnetic pull of the no-voltage release (N). This consists of an electromagnet placed either in series with the field winding of the motor or directly across the line. The arm of the starter is furnished with an iron keeper K, which is gripped by the magnet, when the arm is moved so as to cut out all resistance. This magnet holds the arm against the tension of the spring (H). The strength of the magnet (N) depends upon the current in its wind-

ings which in turn depends upon the line voltage. Should the line voltage diminish so that the current falls below a certain predetermined value, the tension of the spring will exceed the magnetic pull, causing the arm to fly back to the off position, thereby disconnecting the motor from the line.

In connecting up a starting-box to a shunt motor, one side of the line is brought to the point L on the starter. From (L) the current flows through the overload release (O) and starting arm (C) to the first point on the adjustable resistance (R_b); here it divides, part going through the field which is connected to the point F, and the rest through the armature, which is connected to the point A_1. The other points on the armature and field are connected to the opposite side of the line at the point A_3. The line from A_3 to the switch is known as the "common return," since both currents flow back to the line through it.

In connecting a motor for operation, great care must be taken to see that the point on the field from which current flows back into the line is connected to that point on the armature from which current also returns to the line. If point F_3 were connected to A_2, the voltage across the field winding would be that due to the drop across the starting-box. This voltage would diminish as the starting resistance was cut out, causing the motor to draw excessive current from the line due to the weakened field. If, however, F_3 be connected to A_3, full line voltage will always exist across the fields and the field current will have its normal value.

It will be observed that the field connections in the box are so arranged that current will flow through the field winding as soon as the arm is placed on the first of the resistance contacts. This is done in order to give a magnetic flux through the armature from the poles, so that the motor develops a strong torque the instant the armature circuit is completed. This causes it to speed up and develop its C.E.M.F. without any sudden large inrush of current.

Method. — (*a*) Start motor under no load; note value of (1)

voltage across the starting box; (2) voltage across motor; (3) maximum value of current; (4) steady value of current; (5) motor speed for each step on the starting box. Also note field current and line voltage for each reading. Take as many readings as the starter has points.

(*b*) Start motor under load. Connect to line shafting or any other convenient load sufficient to cause motor to draw full load current in starting. Take readings as in (*a*).

Calculate C.E.M.F. of motor for each point on starting box for both (*a*) and (*b*).

Plot curves between motor speed as abscissæ and C.E.M.F. as ordinates for both (*a*) and (*b*), also between points on starting box as abscissæ and armature current as ordinates for both (*a*) and (*b*).

Experiment 13.—(a)—Preliminary Work with a Motor. (b) Operation of a Constant Potential Shunt-wound Motor.

The study of a motor brings out many points of similarity between this class of machines and a dynamo. They are identical in construction, but differ only in the manner of connecting their electrical circuits.

The greatest point of difference lies in their function and application. A dynamo transforms mechanical into electrical energy, while a motor transforms electrical into mechanical energy. A dynamo is necessarily driven from some source of power, while a motor is employed for driving machinery and other apparatus.

A motor can be series, shunt, compound or differentially wound, the first three being identical with the respective windings of the dynamo, the last one differing from the compound in that the series winding reduces the strength of the field when the load increases. The result is that the armature operates at either a constant or increased speed, from no load to full load.

The specific points to be noted under the head of defects are the same as in Experiment 6 (*a*). Note these.

Some of the causes which prevent a motor from operating are added to aid in determining the reason for non-operation.

1. Great overload preventing the turning of the armature.
2. Excessive friction in some part.
3. External or internal circuit open in some place.
4. Wrong connections.
5. Armature revolves at too great speed.
6. Armature revolves in the wrong direction.

Report. — The points to be observed are those contained in the following table. Omit any that are not directly obtainable. Report on the general condition of the machine, as indicated in *a*, *b*, *c*, etc., Experiment 6 (*a*).

Type of Motor.

Constant potential......................
Shunt....................................
Series...................................
Compound ....
Differential..............................
Constant current ....
Series ....

Type of Armature.

Siemens drum ....
Gramme ring.................. ....
Drum wound ring.......................
No. of sections ....
Conductors per section.................
Total number of conductors...........

Armature.

E.M.F. ....
Current ....
H.P. output..............................
Active length............................
Circumference in ft.....................
Speed R.P.M ....
Peripheral speed in ft. per min......

Commutator.

Active length ....
Total length ....
Circumference in ft ....
Peripheral speed in ft. per min......
Total number of bars ....
No. of bars between brushes of opposite polarity.....................
Voltage between bars.................
Width of bars ....
Width of insulation.....................
Kind of brushes ....
Brush area per set ....
Current density in brushes............

Field.

Shunt.....................................
Series.....................................
Compound ....
No. of coils..............................
Method of Winding ....
No. of poles .. ..
Pole pitch ....
Pole width ....
Pole breadth.............................
Pole length..............................

Experiment 13.— (b) — Operation of a Constant Potential Shunt-wound Motor.

Any direct-current, dynamo-electric machine that can be used as a dynamo can be used as a motor; therefore the operation and

testing of a motor is in many respects similar to that of a dynamo. These types of machines are perfectly reversible.

In the case of the motor, electrical energy is supplied to the armature and field coils, the machine being merely an apparatus for converting this energy into mechanical form at the shaft or pulley.

In the case of a dynamo, however, the mechanical energy supplied to the shaft or pulley is converted into electrical energy by the armature's rotation in the magnetic field.

Motors are usually classed according to their field windings, these being known as *series*, *shunt*, *compound* and *differential*. The first three are identical with the corresponding windings of a dynamo, while in the differential form the winding consists of shunt and series coils, the latter acting in opposition to the shunt and weakening the field with the increase of load and current. The net result is the maintenance of a constant speed throughout the load limits.

The following discussion and tests relate only to the shunt motor, the series motor being considered in the next experiment.

The general equation for the current through the armature of a motor is:

$$I = \frac{E - e}{R}. \quad \therefore E - e = IR,$$

which, multiplied by I, gives $EI - eI = I^2R$. The total power supplied to the armature is EI, while the loss in the armature due to this current is I^2R. The useful external work plus the stray power losses is represented by eI. This follows from the conservation of energy and clearly indicates the importance of making the C.E.M.F. of large value. The efficiency of a motor depends upon the relation which exists between the output and input, and as eI minus the stray power losses represents the output, it is important that the value of the C.E.M.F. be high. Another factor of importance in a motor is its *torque* or turning moment. In many types of motors this is of even greater importance than high efficiency, especially when great efforts are

required for short periods. The *torque* of a motor is expressed in *foot-pounds*, or the number of pounds pull at 1 foot radius.

The equation for the C.E.M.F. of a motor is the same as for the E.M.F. of a dynamo

$$e = \frac{2\Phi Nnp}{60 \times 10^8 \times c}.$$

The work done by the armature is

$$Ie = \frac{2\Phi NnpI}{60 \times 10^8 \times c}.$$

The mechanical work done at the pulley is,

Foot pounds per minute $= 2\pi LFN$, while the horse-power developed is

$$\text{HP.} = \frac{2\pi LFN}{33000} = \frac{2\Phi NnpI - K}{746 \times 60 \times 10^8 \times c}.$$

Eliminating constants and similar quantities, it is seen that

$$LF = \Phi IK' = \text{Torque},$$

or that the *torque* is directly proportional to the total current in the armature, the inductors in series and the flux through the armature.

From the equation for the C.E.M.F. it is seen that the speed depends directly upon the C.E.M.F., inversely as the flux and number of inductors. Therefore, if the number of inductors on an armature is fixed, the speed can only be varied by changing the flux or the C.E.M.F. From the fundamental equation for a motor $I = (E - e)/R$, with I and R fixed, the e can be varied only by altering the value of E. Therefore, it follows that the speed also depends upon the value of the E.M.F. at the armature. On a constant potential system, the E.M.F. at the armature can only be decreased, being effected by placing resistance in series with the the armature circuit. If it is desired to increase the speed, the flux must be decreased by decreasing the M.M.F. of the field coils. In a shunt motor this is done by

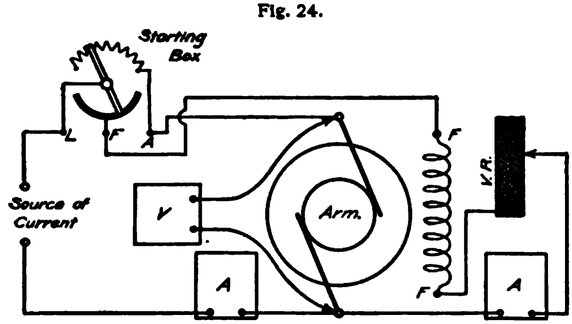
placing suitable resistances in the field circuit, or changing the reluctance of the magnetic circuit as in certain types of variable speed motors. In a differential motor the regulation is automatic.

The reversal of the direction of rotation of a motor armature in all cases, is accomplished by changing the magnetic relation which exists between the armature and field.

If the field magnetization remains fixed, the armature current must be reversed. Or, if the armature connection remains fixed, the field current must be reversed. The usual procedure is to change the armature connection, as it can be more easily accomplished.

In all shunt-wound motors, as in shunt dynamos, it is essential for high efficiency that the armature resistance be made low and the field resistance be made high. The I^2R losses in both circuits will then be a minimum, and the regulation of speed will be most perfect.

Fig. 24.



As the field coils are made of high resistance, they are connected directly to the circuit from which the machine is to be operated, while the armature, being of low resistance, needs to have starting resistance placed in series with it. This resistance will permit enough current to pass to start the armature, being eventually cut out of the circuit, thus placing the full E.M.F. of the circuit across the armature. As was shown previously, the generation of the C.E.M.F. prevents any excessive current from passing through the low resistance armature.

This starting resistance is quite necessary for the reason that if the low resistance armature were connected directly to the E.M.F. a large inrush of current would occur and would blow the fuses or circuit-breakers.

The connections for operating a shunt motor are given in Fig. 24, separate ammeters being inserted so as to measure the armature and field currents.

The following paragraphs contain elementary tests which can be undertaken to prove the discussion which precedes.

1. Measure the resistance of the field coils by the fall of potential method or with the Wheatstone bridge, and the armature by fall of potential.

2. Make the proper connections for operating a shunt motor using a suitable starting box and placing an ammeter in both armature and field circuits and a voltmeter across the armature terminals. On starting up note the fluctuations in the *current* as the starting resistance is cut out. Note the speed and adjust the position of the brushes so that the *minimum* speed at no load is obtained and also note this is the position of minimum sparking. It is known as the *neutral point.*

3. Note the number of *watts* necessary to operate the motor at *no load.* It is the product of the E.M.F. of the circuit and the sum of the armature and field currents. This amount of power is required to overcome all friction and other internal losses at no load.

4. Determine from the instrument readings and the equations given on page 60 the value of the C.E.M.F. at no load. Increase the load on the motor and note what changes in speed occur. From these can be calculated the percentage by which the C.E.M.F. is decreased. Explain the fact that only a small current passes through the armature when running without load and that this current increases with load on the motor.

5. Study of speed regulation. (*a*) With the armature running with no load, move the brushes to and fro a *short* distance about the commutator, recording the resultant variations in speed. This is a limited method of regulation and if carried too far may

result in bad sparking. The number of effective inductors is altered, thus varying the speed.

(*b*) In the field circuit is inserted a rheostat, by means of which the field current is varied and the flux altered. The speed varies almost inversely as the flux. Do not permit the field circuit to be opened for the armature will act as a direct short circuit across the line.

Plot a curve between field currents and speeds.

(*c*) In the armature circuit is placed a variable resistance which will alter the E.M.F. at the armature terminals and vary the speed. Plot a curve on the same sheet with the (*b*) curve between armature E.M.F.'s and speeds. Note and record the effect upon the speed of increasing the load under these conditions and explain the result.

(*d*) Investigate the methods of reversing the direction of rotation of the armature.

Report to contain diagram of connections, observations, curve sheets and all explanations.

Experiment 14. — Commercial Efficiency of a Shunt Motor using a Brake.

This test illustrates one of the simplest combined electrical and mechanical methods for determining the efficiency of an electric motor. In order to insure the accuracy of the results, it is necessary to exercise considerable care in making the readings of the various instruments, especially the speed recorder.

The Prony brake, which may be employed in this experiment, in its simplest form, consists of a lever arm of wood or metal with suitable means for clamping it to the pulley or fly wheel of the machine under test, thus tending to make it rotate due to the friction of the clamp on the pulley. The tendency to pull or rotate is measured by a spring balance or weights attached to the end of the lever arm.

Fig. 25 illustrates a simple form of this brake, applicable to the testing of small motors. The brake is made of two wooden pieces held together by bolts with wing nuts, by means of which the pressure on the surface of the pulley can be adjusted, thus

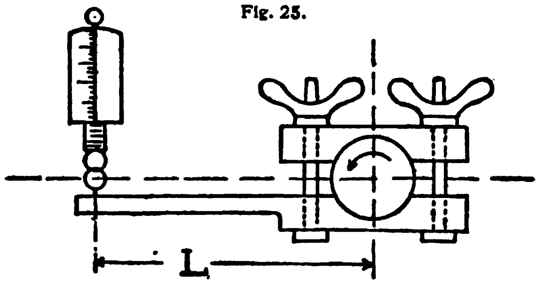
altering the force due to friction and the pull at the end of the lever arm. By measuring this pull, the speed of rotation, and the length of the lever arm, the power developed can be readily calculated.

Method. — Work is equal to the product of force and distance or FL, and power is equal to work divided by time, or

$$\frac{FL}{T} = Fv, \text{ where } v = \text{velocity.}$$

The distance L, from the center of the shaft to the point of application of the force resisting the tendency of the lever to rotate, is ascertained by careful measurement. In one revolution of the

Fig. 25.



pulley, the distance through which the point of application of the force would travel if allowed to do so, would be equal to $2\pi L$, and if the number of revolutions per minute is N, the power, in foot-pounds per minute, is

$$\text{Power} = 2\pi LNF.$$

To reduce this to horse power, it is necessary to divide by 33 000, the number of foot pounds per minute equivalent to one horse power.

The band or differential brake is another type of brake used to load apparatus for testing purposes. It consists of a canvas belt so arranged as to partly surround the pulley of the motor. The load is adjusted by varying the friction between the belt and the pulley; this is accomplished by means of the hand-wheel (H) and threaded rod (S). Fig. 26 shows a sketch of this type of brake.

Before starting the brake test allow the belt to hang free from the pulley, hold steelyard horizontal and note reading on the spring balance. To load the motor, adjust the position of the frame until the belt, while surrounding the pulley, has its sides parallel and vertical. After this is accomplished adjust the load by turning the hand-wheel.

The radius at which the force developed is acting is found by taking the radius of the pulley plus one-half the thickness of the belt. The force or pull developed is equal to the difference between the readings of the steelyard and spring-balance less the initial reading of the spring-balance, which is determined as described above. The weight on the steelyard must be so adjusted as to cause it to be perfectly horizontal before taking any readings. Balance is maintained, while reading the instrument, by adjusting the hand-wheel. The pulley should rotate in the direction shown by the arrow, so that it will pull downward on the steelyard.

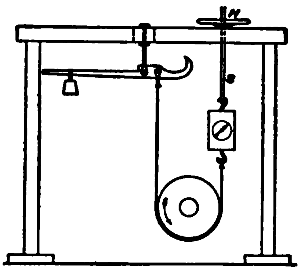


Fig. 26.

To employ either of these methods in the determination of the efficiency of an electric motor, it is necessary to take the following readings:

1. E.M.F. at the terminals of the motor.
2. Ampères in the external circuit.
3. Speed at every load.
4. Pull in pounds at end of lever arm.
5. Length of lever arm.

Note these as in Table XI.

Report. — 1. Determine the efficiency of the motor assigned, at approximately $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$, $\frac{7}{8}$, full load and $\frac{1}{4}$ over load, plotting a curve showing the commercial efficiency of the motor. Use watts or horse power output for abscissas and commercial efficiency for ordinates.

2. Determine the values of the *Torque* and plot in the form of a curve on the same sheet as the efficiency curve, using values of current for ordinates and values of the torque for abscissas.

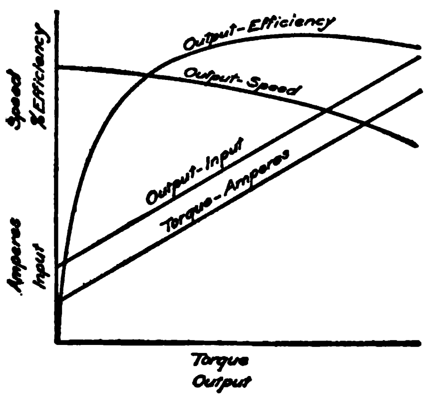
TABLE XI.

A	B	C	D	E	F	G	H	I	J	K
E.M.F.	Amps. in Arm.	Amps. in Field	Total Amps.	R.P.M.	Lbs. Pull = P	Torque	Watts Input	H.P. Input	H.P. Output	% Efficiency
			B+C			P×L	A×D	H/746	$\frac{2\pi LNP}{33,000}$	J/I×100

3. Plot a curve on the same sheet, showing the relation between speed and horse power output, using values of the output for abscissas and speed for ordinates.

4. Plot curve on same sheet between values of H.P. input and

Fig. 27.



H.P. output, using the first for ordinates and the second for abscissas.

Fig. 27 shows the forms of the various curves. From the appearance of these curves, conclusions as to the performance of the machine are to be drawn.

Experiment 15. — Stray Power Method for Determining the Commercial Efficiency of a Shunt Motor.

This method consists in measuring the sum of the core and friction losses at the different speeds and field strengths which occur in operating a machine throughout its range of load. The two great advantages of the method are (*a*), that only a small per cent. of the total capacity of the machine is employed, thus saving energy, and (*b*), the accuracy secured is greater than when using a combined mechanical and electrical method.

The test differs in a number of ways from those employing mechanical dynamometers, the most important difference being that electrical measurements only are employed. Further, instead of the whole output and input being measured, the value of the stray power losses only are determined. The first important advantage of this method arises in not being compelled to operate the machine at full-load conditions for long periods, thereby wasting energy; in the second place, the stray power losses, which usually form a small per cent. of the total input of the machine, are measured directly and very accurately. In case any error is made in their determination, it forms a small per cent. of a small per cent. (as the total stray power losses are generally small in amount) and therefore does not offer the same opportunity for vitiating the results as does a like per cent. error while measuring the efficiency by any other combined electrical and mechanical method, involving the measurement of the total input and output. Therefore this method is recommended for exact determinations of the commercial efficiencies of direct-current dynamos and motors. The most important disadvantage is that the faults at full load are not brought out.

The losses in a dynamo or motor can be divided as follows:

1. ELECTRICAL OR COPPER LOSSES.

(*a*) I^2R in armature conductors.
(*b*) I^2R in brushes and brush contacts.
(*c*) I^2R in armature leads.

(*d*) I^2R in field windings, shunt and series.

In the case of a self-excited dynamo, or a motor having a field rheostat, the losses in the field rheostat are to be added to the other losses to give the total loss.

2. Stray Power Losses.

(*e*) Bearing friction and air friction or windage.

(*f*) Friction of brushes on commutator.

(*g*) Hysteresis in the armature iron.

(*h*) Eddy current loss in iron of armature and pole tips and copper of armature.

$\left.\begin{array}{l}(g)\\(h)\end{array}\right\}$ Core losses.

When a machine is completed it is difficult to measure each element of the stray power loss, so they are measured collectively and added to the *copper losses* to give the total loss.

The friction losses vary directly as the speed within the limits between which the machine is operated. The hysteresis loss varies as the speed and as the 1.6 power of the induction in the armature iron. The eddy current loss varies as the square of both the speed and the induction. Consequently if either the field strength or the speed changes, the stray power loss is altered. Therefore it is essential to reproduce exactly the conditions of speed and field strength under which the machine operates at any load.

The core loss is also affected by the armature current of the machine since this produces a flux which affects the density and distribution of the total magnetic flux through the armature.

To determine the stray power losses corresponding to a certain load for any given machine, run the machine at no load under the same conditions of speed and field strength as when loaded. The stray power losses at no load will be practically the same as when the machine was loaded. The effect of armature reaction is less at no load, which causes a difference in the value of the core loss as above stated, but this difference is usually so small as to be negligible.

The total input of a motor, operating at no load, is consumed

by the I^2R losses in the armature circuit and field winding and in stray power. Hence if the total I^2R losses for this no load value of armature and field currents be subtracted from the no load input, the remainder will give the stray power loss for the corresponding load.

Let E_a = voltage across armature at no load. This must be such as to duplicate the speed of the motor under load.

" I_a = current in armature at no load.

" E_f = voltage across field winding at no load.

" I_f = current in field winding at no load which is made same as when motor was under load.

" R_a = hot resistance of armature circuit at no load.

" R_f = hot resistance of field winding at no load.

Then $I_a^2R_a$ = watts lost in armature circuit at no load.

$I_f^2R_f$ = watts lost in field winding at no load $= E_fI_f$ since

$$R_f = \frac{E_f}{I_f}.$$

Total no load input $= E_aI_a + E_fI_f$.

Hence $E_aI_a + E_fI_f = I_a^2R_a + I_f^2R_f +$ stray power loss; or stray power loss $= E_aI_a + E_fI_f - [I_a^2R_a + I_f^2R_f]$.

Since $E_fI_f = I_f^2R_f$

Stray power loss $= E_aI_a - I_a^2R_a$.

This equation shows that the stray power loss corresponding to any load may be found by subtracting the no load armature I^2R loss from the no load armature input, if the speed and field strength be the same as for the load condition.

If the stray power loss, the armature current and field current corresponding to each condition of load on a motor are known, its efficiency may be calculated as follows:

$$\text{Efficiency} = \frac{\text{Input} - \text{Losses}}{\text{Input}}.$$

Input for each load $= E(I_a' + I_f)$.

Losses for each load $= I_a'^2R_a' + EI_f +$ stray power (corresponding to this load).

It must be borne in mind that I_a', the value of the armature current for this loaded condition of operation is altogother different from the armature current used in the stray power test. The values of the armature currents in the stray power test should not be employed in calculating efficiencies.

E is the line voltage across motor.

Hence per cent. of efficiency.

$$= 100\left(\frac{E[I_a' + I_f] - [\text{stray power} + I_a'^2R_a' + I_f^2R_f']}{E[I_a' + I_f]}\right)$$

$$= 100\,\frac{EI_a' - [\text{stray power} + I_a'^2R_a']}{E[I_a' + I_f]}.$$

$R_a' =$ hot resistance of armature circuit under load..

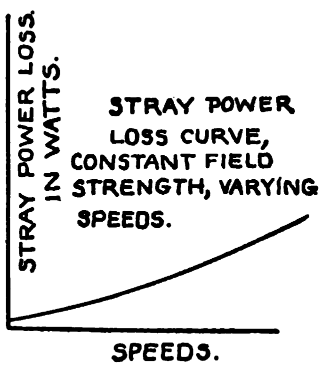
$R_f' =$ hot resistance of field circuit under load. This includes the resistance of the field rheostat if one is employed under operating conditions.

It is seen that if the speeds, field and armature currents corresponding to different loads on the motor be known, its efficiency can be calculated for all loads if the stray power losses corresponding to each load have been determined as previously described.

If the line voltage be constant and the field resistance is not varied, the field current will be practically constant for all loads, and the speed is the only factor which will affect the stray power loss, if the effect of armature reaction is neglected. For this condition, the stray power losses for different loads may be plotted in the form of a curve as shown in Fig. 28, and the proper value of the stray power loss corresponding to any load can be easily ascertained from this curve. If both speed and field current vary the stray power losses can not be put in the form of a curve, but should be tabulated.

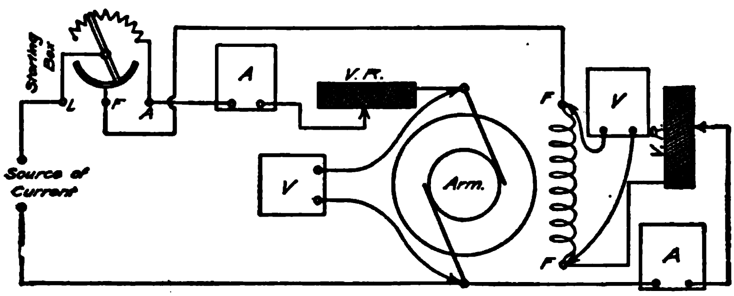
Method. — 1. The resistance of the armature, fields and rheostats are determined, preferably at that temperature which the machine has under operation. If not, correction can be made by using the proper temperature coefficient.

Fig. 28.



2. The connections are made as in Fig. 29. There should be variable resistances in both armature and field circuits besides a proper starting box. The armature ammeter need be of sufficient capacity to measure only a small fraction of the normal full load current. The voltmeter should have a range equal at least to the voltage of the machine.

Fig. 29.

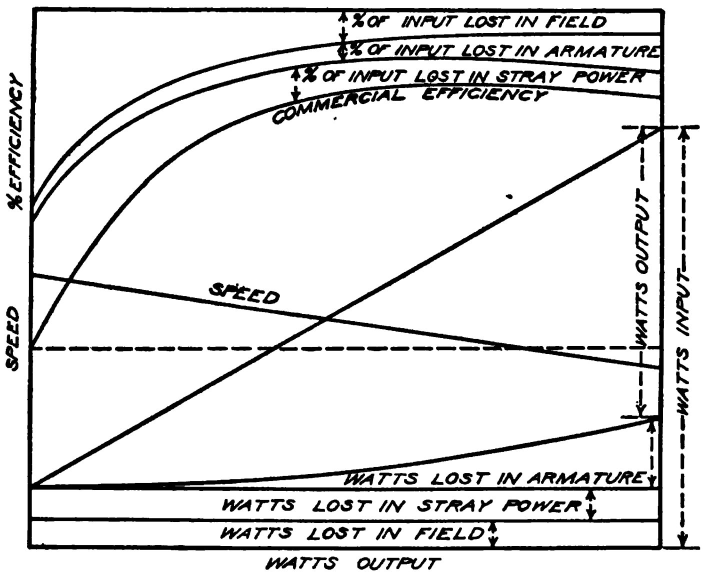


3. The machine whether dynamo or motor, should be run *as a motor*, without load, at those speeds and the field strength corresponding to each speed at which it ran when operating under

working conditions from full load to no load. The armature voltage should have such a value as to give the speed desired. This voltage is adjusted by means of the variable resistance in series with the armature circuit.

Part (*a*) Table XII. gives the values of the different quantities involved for full load condition of operation. Columns *A*, *B*, *C*, *D* are obtained from the data of Experiment 14, column (*I*) in part (*a*) is obtained from column (*Z*) of part (*b*). The remaining columns of part (*a*), Table XII., are all calculated when the above quantities are known. Part (*b*) of Table XII. shows the readings and calculations to be made in order to determine the stray power loss corresponding to each load. The values of speed

Fig. 30.



and field current are obtained by referring to columns (*A*) and (*C*) of part (*a*).

Report.—All observations tabulated and a curve sheet as shown in Fig. 30.

Present conclusions.

TABLE XII.

(a)

MOTOR RUNNING UNDER LOAD.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R.P.M.	Line Volts	Field Current	Arm. Current	Total Current	Watts Input	Watts Lost in Arm.	Watts Lost in Field	Stray Power Loss	Total Losses	Watts Output	% Efficiency	% Input Lost in Field	% Input Lost in Arm.	% Input Lost in Str. Power	Total % Input = 100
				$C+D$	$E \times B$	$D^2 \times R_a$	$B \times C$	$Z_{(b)}$	$G+H+Y_{(b)}$	$F-J$	$K/F \times 100$	$H/F \times 100$	$G/F \times 100$	$I/F \times 100$	$L+M+N+O$

(b)

MOTOR RUNNING LIGHT.

Q	R	S	T	U	V	W	X	Y	Z
R.P.M.	Arm. Current	Field Current	Volts Across Field	Volts Across Arm.	Total Watts Input	Watts Lost in Field	Watts Lost in Arm.	Total No Load Copper Losses	Stray Power Loss
$A_{(a)}$		$C_{(a)}$			$R \times U + S \times T$	$S \times T$	$R^2 \times R_a$	$W+X$	$V-Y$

Hot Resistance of Armature = R_a = ... Ohms

Hot Resistance of Field = R_f = ... Ohms.

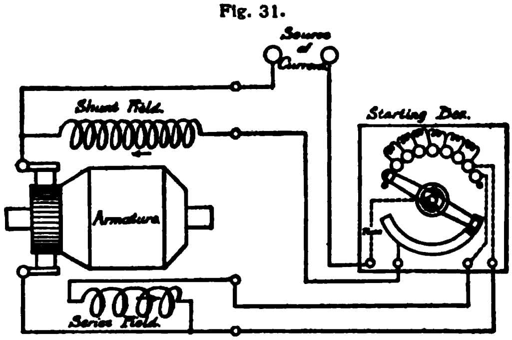
Experiment 16. — Operation of a Differential Motor.

A differential motor is one whose field coils are divided into two parts, shunt and series, being similar in this respect to a compound dynamo.

Instead of the series winding increasing the flux with increase in load, its action is to decrease or weaken it in order to produce a constant speed under all conditions, the latter being the object to be accomplished in the design of such a motor.

The arrangement of the circuits is shown in Fig. 31.

Fig. 31.



The starting box is arranged to start the machine as a shunt motor. After full speed has been attained the series field is connected in the armature circuit. This is necessary in order to avoid the reversal of the armature due to a large starting current passing through the series turns and overcoming the shunt field excitation. In the case of very heavy overloads the series ampère-turns might be sufficient to neutralize the effect of the shunt ampère-turns and cause a short circuit. For this reason the shunt motor is preferable. A shunt motor may be designed so that its armature reaction may accomplish the same constancy in speed as the differential motor is designed to do.

The following demonstration will indicate the automatic regulation which occurs with the flux through the armature. The condition sought is constant speed at all loads.

The work performed by the motor is:

$$HP = \frac{2\pi LFN}{33000} = \frac{eI - \text{stray power losses}}{746}$$

$$= \frac{2\phi NnpI - \text{stray power losses}}{746 \times 60 \times 10^8 \times c}.$$

Omitting constants, we have the torque equal to

$$T = LF = \phi IK'.$$

With increasing loads the current in the armature must increase, as the torque depends upon the flux and current. In order that the current may increase, the C.E.M.F. must decrease as shown in

$$I = \frac{E - e}{R}$$

where E and R are constant;

$$e = \frac{2\phi Nnp}{60 \times 10^8 \times c}.$$

Eliminating constants, we find, $e \propto \phi$ $\therefore$ current varies inversely as the flux.

In order that the speed may remain constant for all loads it is seen that it is necessary to reduce the flux in proportion to the increase in armature current. This is somewhat modified in practice, due to the effect of armature reaction.

Method. — Operate the machine as indicated in Experiment 13(*b*). Note speed regulation carefully from no load to full load. Plot curve between watts input and speeds, constant E.M.F. at motor terminals.

Report. — All measurements and observations. Explanation of operation of machine. Connections. Curve of speed regulation.

Experiment 17. — Commercial Efficiency of a Differential Motor using a Brake.

The idea involved in the test is similar to that governing the test of a shunt motor.

The method is the same and requires the same set of readings as indicated in Table XI., Experiment 14.

Follow instructions as given in Experiment 16 while operating this type of motor.

Report. — Follow the method given in Experiment 14 in presenting report of this test. Give all conclusions.

Experiment 18. — Operation of a Series Constant Potential Motor.

The series motor on which this investigation is to be conducted is designed for use in street railway service and is intended to operate with a potential of 500 volts at its terminals. In a series motor the field winding and the armature are placed in series, the same current passing through both. The cross-section of the wire on the field is large and the number of turns is small as compared with the shunt motor field winding. Therefore the resistance of the field is small and the I^2R loss in this part of the circuit is kept low. The armature resistance is also made as small as possible in order to reduce the I^2R loss and to obtain good speed regulation.

The main point of difference between this type of motor and the shunt motor is that the latter maintains a nearly constant speed with a varying load, whereas the speed of a series motor varies greatly with the load. When the load increases the speed decreases, and when the load is decreased the speed rises, and if the external mechanical work done by the motor is zero and the resistances due to the friction of the bearings and commutator are not great, the speed may attain a high and dangerous value. The speed will rise to a point where the power input is just balanced by the internal losses and the friction in bearings and gearing.

As has been shown, the speed of a motor depends upon (*a*) the number of lines of force through the armature or strength of field, (*b*) the E.M.F. at the brushes, and (*c*) the number of conductors in series with each other on the armature. The latter is fixed once for all if the brushes are fixed in position, so that the

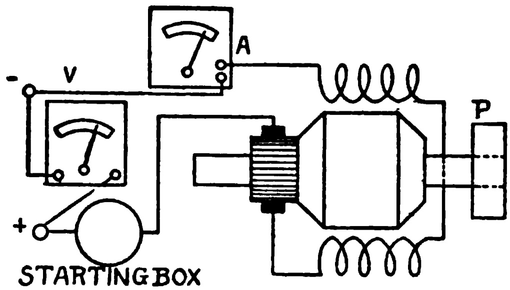
speed depends upon the other two factors. In the case of a shunt motor the field is of nearly constant strength, so that the speed will be dependent upon and nearly proportional to the E.M.F. at the brushes.

In a series motor both the field strength and E.M.F. at brushes vary with the work done, so that the speed may vary within wide limits.

In the shunt motor as the field is constant, the torque will be nearly proportional to the current in the armature. In the series motor the torque, being the product of field strength and armature strength, is greatest at starting when the largest current is passing through the armature. This is the most valuable characteristic of a series motor.

As the load on the motor decreases the current decreases, producing thereby a weaker field and at the same time permitting an increase of E.M.F. at the armature terminals or brushes.

Fig. 32.



By referring to Fig. 32, the above changes can be more readily followed.

When the load is decreased at *P*, the pulley or car wheel, the resistance to rotation becomes less and the armature speeds up; this increases its C.E.M.F. and consequently reduces the current, as in a shunt motor. In the case of the series machine, however, this decrease of current also weakens the field, necessitating a further increase in speed to keep the C.E.M.F. up to, and the current down to, their proper values; the machine always auto-

matically adjusting its C.E.M.F. so as to take a current proportional to the load.

If the load increases a larger current is required, therefore the speed falls and the C.E.M.F. decreases sufficiently to permit the necessary current to flow. When the load is reduced a smaller current is required, therefore the armature speeds up and increases its C.E.M.F. and reduces the current to the proper value.

These variations in speed are, however, as has been already pointed out, much greater in the series than in the shunt motor on account, not only of the variations in the field strength with the variations in the load, but also to the varying E.M.F. across the armature terminals.

When the armature is held stationary the series motor exerts its maximum torque, for the current obtained from a constant potential source is a maximum, its value being simply dependent on the ohmic resistance of the windings. This feature is very desirable in the application of motors to any duty where heavy starting torque is required, as in the case of elevators, hoisting apparatus and electric traction.

In order to regulate this type of motor it is necessary to use an external resistance in series with the machine, this being decreased as the load is applied and inserted as the load is decreased. From the above it will be understood that the speed and torque vary inversely. The current in a series motor is equal to

$$I_t = \frac{E-e}{R_a + R_f}$$

and the counter E.M.F.,

$$e = E - I_t(R_a + R_f)$$

where

R_a = resistance of armature.

R_f = resistance of field.

If

S_a = number of turns in the armature.

S_f = number of turns in the field.

speed depends upon the other two factors. In the case of a shunt motor the field is of nearly constant strength, so that the speed will be dependent upon and nearly proportional to the E.M.F. at the brushes.

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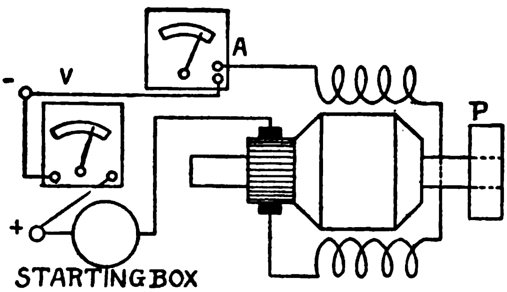
Fig. 32.



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$$I_t = \frac{E-e}{R_a + R_f}$$

and the counter E.M.F.,

$$e = E - I_t(R_a + R_f)$$

where

R_a = resistance of armature.

R_f = resistance of field.

If

S_a = number of turns in the armature.

S_f = number of turns in the field.

$K =$ a constant.

then

$$\text{Torque} = KI^2(S_a \times S_f),$$

that is, the torque is proportional to the *square* of the current. This however is only true at low magnetizations.

Operation.

1. Determine the resistance of the field and armature by fall of potential method *before operating.*

2. Operate the motor from 115-volt circuit in order to study its action with change of load and also with change of E.M.F. applied. Determine C.E.M.F. at the speeds and currents noted.

Connections are shown in Fig. 32.

Report. — Observations, connections, full explanations and conclusions, curves between speeds as abscissas and volts at terminals and currents as ordinates.

Experiment 19. — Commercial Efficiency of a Series Constant Potential Railway Motor Using a Prony Brake.

The object of this test is to determine the commercial efficiency of a series constant potential motor. For this purpose a 500 volt railway motor is to be used. The motor is provided with a shaft in place of the usual axle, with the axle gear mounted upon one end of it. At the other end is a pulley on which may be placed a brake as illustrated in Figs. 25 or 26. Either type of brake can be used.

Method. — The motor is to be operated with a constant E.M.F. at its terminals of 500 volts. Connections are to be made as shown in Fig. 32.

(Exercise great care not to come in contact with the 500 volt circuit.)

To carry out the test make the following readings:

(*a*) Measure the power required to operate the motor at no load with the brake entirely free from the pulley. Note and record speed.

(*b*) Add load by means of the brake and with each increase adjust the E.M.F. to 500 volts.

(*c*) Carefully record speed, weights or scale readings, volts and amperes, after having brought the brake to a satisfactory balanced condition by means of the adjusting screws. Follow the readings as shown in Table XIII.

TABLE XIII.

A	B	C	D	E	F	G	H	I
Terminal Volts	Current	R.P.M.	Net Pull in Pounds	Torque	Watts Input	H.P Input	H.P. at Brake	% Efficiency
			$=P$	$P \times L$	$A \times B$	$F/746$	$\frac{2\pi LNP}{33000}$	$H/G \times 100$

Length of lever arm in ft. = 31.5″.

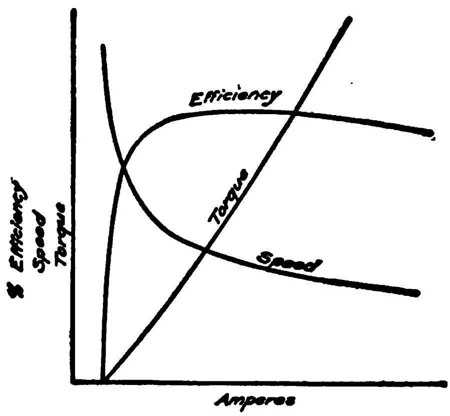
Report. — From the measurements made:

(*a*) Calculate the commercial efficiency of the motor at about ten points from no load to full load.

(*b*) Determine the torque for each value of the current.

(*c*) Plot on one sheet the relation between (1) efficiency and amperes, (2) torque and amperes, (3) speed and amperes as shown in Fig. 33.

Fig. 33.



Draw conclusions from the results and explain any attendant phenomena. Give diagram of all connections.

Experiment 20. — Stray Power Method for Determining the Commercial Efficiency of a Series Constant Potential Motor.

The determination of the efficiency of a series constant potential motor by the stray power method is similar to that of the shunt motor as given in Experiment 15. The stray power losses vary with the speed and field strength, so that in determining them it is essential to secure corresponding conditions of speed and field strength. The results which were obtained in the test of this type of motor by the Prony brake are to be referred to in this experiment, in order to ascertain the corresponding values of the speeds and field currents.

As at each value of the output, the speed and field current were different, the stray power loss for each output will have a different value. Therefore, it is essential to operate the armature at the speeds which occurred in the Prony brake test, with the field current set at the value which was required at that point.

The watts input at the armature is measured, $E_a \times I_a =$ watts input, and the $I_a^2R_a$ loss occasioned by this current is subtracted from the input. The remainder represents the stray power losses under the conditions of speed and field strength.

Then if to this value of the stray power loss are added the I^2R losses in the armature and fields corresponding to the load for which the stray power is calculated, we will have the total losses in the motor. The total input being known, it is necessary to subtract the value of the corresponding losses from it to determine the output, as

$$\text{Input} - \text{losses} = \text{output.}$$

Then the per cent. efficiency is equal to the

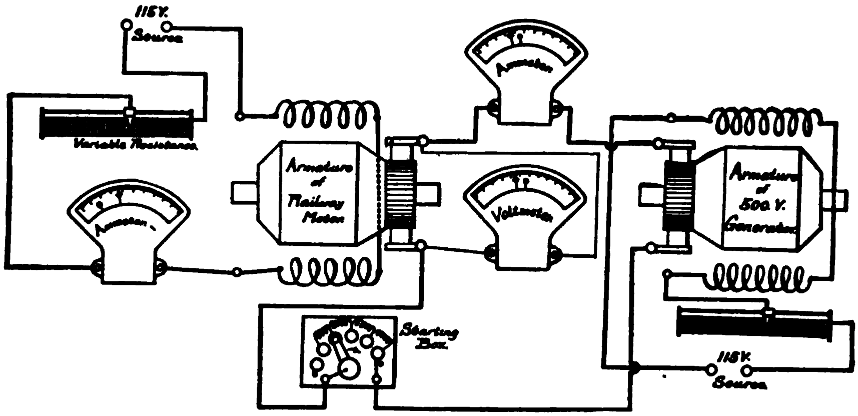
$$\frac{\text{Input} - \text{losses}}{\text{input}}.$$

The determination of the stray power losses can be made for

all values of load, and the efficiency accurately determined for such values.

Method. — Arrange the connections as shown in Fig. 34, using instruments of the same range as in Experiment 21. The field

Fig. 34.



is to be separately excited, using a suitable variable rheostat to adjust the current to the proper values. The armature is to be operated from a 500-volt circuit, the E.M.F. being adjusted so that the armature, with any given current through the fields, will have the proper speed. Then the watts required to operate the armature at this speed, minus the I^2R loss due to the corresponding armature current, will equal the stray power loss. The stray power losses for all speeds recorded in the Prony brake test are to be determined and the efficiencies calculated.

Report. — Present all measurements and calculated results as shown in Tables XIV., *a* and *b*:

TABLE XIV., *a* — NO LOAD.

A.	B.	C.	D.	E.	F.	G.	H.	
Volts at Armature	Amperes in Armature	Amperes in Field	Watts I^2R in Armature	Watts I^2R_f in Field	Watts delivered to Armature = A×B	Stray Power Loss = F−D	Speed.	
							Tachometer	Revolution Counter

TABLE XIV., *b*—FULL LOAD.

A.	B.	C.	D.	E.	F.	G.	H.		I.	J.	K.	L.	M.
E.M.F.	Amperes.	Watts Input. A×B	I^2R in Armature.	I^2R in Field.	Stray Power Loss.	Total Losses =D+E+F.	Speed. Tachometer.	Speed. Revolution Counter.	Watts Output =C−G.	Per Cent Efficiency =I/C.	% of Input Armature I^2R Loss =D/C.	% of Input Field I^2R Loss =E/C.	% of Input Stray Power Loss =F/C.

Present results in curves as shown in Fig. 30, Experiment 15, and give conclusions. What if any error is present in this method as used with this type of motor?

Experiment 21.—Stray Power Method for Determining the Commercial Efficiency of a Dynamo.

The above method as applied to a dynamo is similar to that of Experiment 15 as used with a motor (the dynamo is now operated as a motor). It is necessary to secure corresponding conditions of speed and field current, for the reason that the stray power losses vary with them. The data which are obtained from the operation of a dynamo at a constant voltage and speed from no load to full load current are to be referred to in order to ascertain the corresponding conditions of the quantities to be measured. If these are not available the data can be secured by operating the machine as a dynamo as in Experiment 7, Part 5.

After the field current has been adjusted to the proper value, the corresponding speed is secured by adjusting the E.M.F. at the armature terminals. The armature terminal E.M.F. and current are noted, thus giving the watts, from which is to be deducted the $I_a^2R_a$ loss in the armature due to this current to get the *stray power loss.* This method can be followed for all variations and the efficiency calculated as follows:

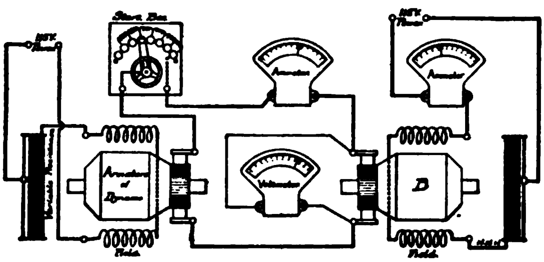
$$\text{Output} + \text{losses} = \text{input}.$$

$$\frac{\text{output} \times 100}{\text{output} + \text{losses}} = \frac{\text{output} \times 100}{\text{input}} = \text{efficiency}.$$

Therefore as the electrical outputs are known, the losses can be calculated and added to the outputs to give the corresponding mechanical inputs at the shaft or pulley.

Method. — The connections for this test are shown in Fig. 35.

Fig. 35.



There is a rheostat in the field circuit to adjust the current to the proper values.

It is necessary to have available a higher voltage than that which the dynamo ordinarily generates in order that it shall run as a motor at the speed at which it is driven as a dynamo. For this purpose a higher voltage dynamo can be employed, or two lower voltages can be put in series. If another dynamo is used its field current can be so regulated that the proper voltage for operating the motor at its correct speed can be easily obtained, and without the use of a variable resistance (*VR*) in the armature circuit of the motor.

Measure the armature current and terminal E.M.F., calculate the watts necessary ($I \times E$) and subtract from the result the I^2R loss due to this current. The remainder is the stray power loss for that condition of speed and field strength. Add to this all the I^2R losses *under load*, giving the *total losses*. Add this to the output at the given load to find the input. Then the

$$\frac{\text{output} \times 100}{\text{output} + \text{losses}} = \text{efficiency}.$$

Report. — Give all measurements and results as shown in Table XV., *a* and *b*, and present curve sheet containing results as in Fig. 30. Give conclusions from the form of the curves and any phenomena noticed during the tests. Is there any error in this method?

Experiment 22. — Determination of the Commercial Efficiency and Other Characteristics of a Motor-Dynamo.

A motor-dynamo consists of a motor driving a dynamo with the armatures located upon the same shaft. In the case of direct

TABLE XV, *a*.

A.	B.	C.	D.	E.	F.	G.	H.
Volts at Armature Terminals	Amperes in Armature	Amperes in Field.	Watts $I_a^2 R_a$ in Armature	Watts $I_f^2 R_f$ in Field.	Watts delivered to Armature A×B	Stray Power Loss F–D.	Speeds

TABLE XV., *b*.

I.	J.	K.	L.	M.	N.
Total Copper Losses under Load.	Total Losses in Watts G+I.	Efficiency equal to Output and Loss / Output+Loss	% of Input Loss in Fields.	% of Input Loss in Armature	% of Input Lost in Stray Power = G/Input

current machines there may be an armature with two commutators and two independent windings, the armature revolving in one field; or there may be two entirely independent armatures on the same shaft, each having its own field. The latter arrangement is much to be preferred to the former, as better control of the speed and generated E.M.F. can be secured. Each field can be regulated independently, whereas in the single field type no satisfactory regulation can be obtained.

With direct current machines the motor armature with its field are built to operate on the power or lighting circuits, while the dynamo armature is designed for many purposes, such as boosting the E.M.F of a feeder by some small amount, generating an E.M.F. which may be used directly, or be put in series with the main line to charge storage batteries. The principal idea is to

obtain a voltage which is different from and independent of the station or line voltage.

In the case of the type with two independent armatures and fields, the dynamo may be wound with a shunt, compound or differential field, or may be separately excited from an outside source.

The machine to be tested is of the single field type with two armature windings on the same core, and two commutators, one on each end of the armature.

The commercial efficiency of the set, as well as the external characteristic of the dynamo end are important quantities to be found, and the principal tests will be to plot these. The external characteristic gives the inherent regulation of the E.M.F. of the dynamo. The commercial efficiency shows the relation at different outputs between the output and the input.

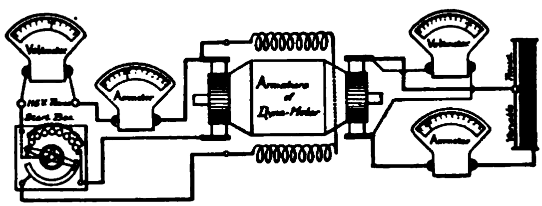
As the input is equal to the total watts supplied to the motor end, $E_m \times I_m$, while the output equals the product of the E.M.F. and current measured at the terminals of the dynamo armature, the

$$\text{Per cent. Efficiency} = \frac{I_d E_d}{I_m E_m};$$

I_m equals the sum of the armature and field currents of the motor.

Method. — Determine the resistance of both armatures and the field coils. Connect the machine as shown in Fig. 36 and see

Fig. 36.



that the brushes on both armatures are set in their proper position.

Make the observations as shown in Table XVI. *a* and *b*, and

TABLE XVI., *a*.

A	Motor.			Dynamo.			H	I	J.
	B	C	D	E	F	G	$\frac{\text{Watts Dynamo}}{\text{Watts Motor}}$ = Commercial Efficiency	I^2R in Motor Armature	I^2R in Field.
Speed.	E.M.F.	Amperes.	Watts.	E.M.F.	Amperes.	Watts.			

TABLE XVI., *b*.

K	L.	M.	N.	O.	P.	Q.
I^2R Dynamo Armature	Stray Power Losses.	Total Losses	% of Input Motor Arm. I^2R Loss $= \frac{I}{D}$	% of Input Field Loss $= \frac{J}{D}$	% of Input Dynamo Arm. I^2R Loss $= \frac{K}{D}$	% of Input Stray Power Loss $= \frac{L}{D}$

calculate the commercial efficiency and other percentages called for in Tables.

Report. — All observations and calculated results. Set of curves as shown in Fig. 37. Conclusions.

Experiment 23. — Operation of Shunt Dynamos in Parallel.

In the operation of a central station it is often necessary to run shunt dynamos in parallel, giving a current output equal to the combined capacity of the machines. This experiment is intended to point out the various precautions which must be observed in order that no accident shall happen to the machines or to the circuits to which they are connected and to show the division of current between machines under different conditions of load.

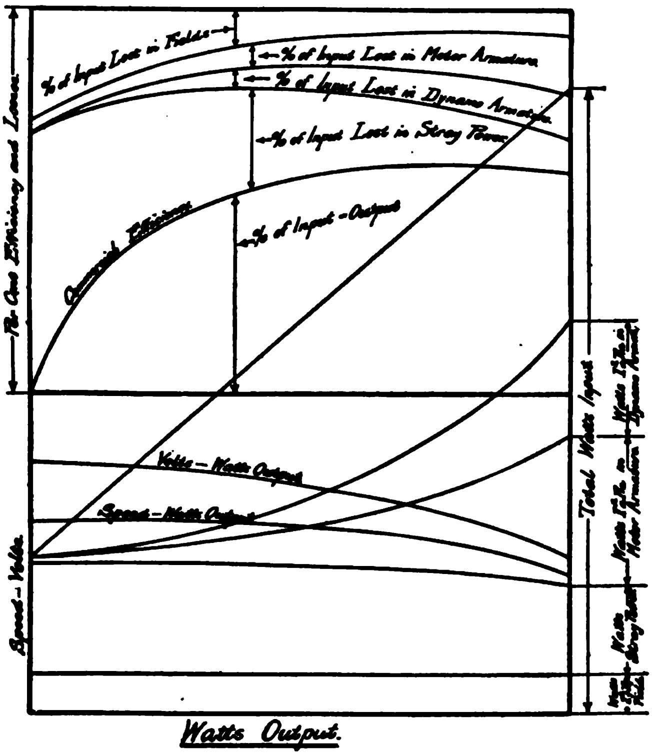
The three essential points are:

1. The dynamos must first be brought up to their proper speeds.
2. Their fields excited so as to produce the same E.M.F.'s at the dynamo terminals.

3. The connections must be arranged so that like polarities are brought together on the same bus-bars or mains.

It is essential that the speed be properly adjusted; otherwise, with the other conditions fulfilled, the machine whose speed is varying widely will either throw its load upon the other machines or will take so much from the others as to open the circuit-breakers or blow the fuses.

Fig. 37.

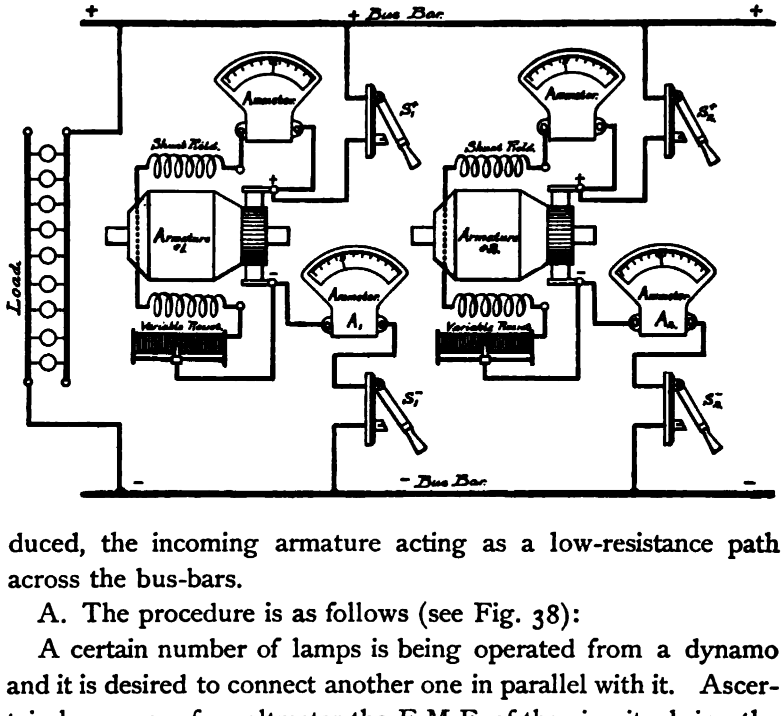


The E.M.F. of the incoming machine should be the same as the E.M.F. of the bus-bars or other machines. If its E.M.F. is much too low, a heavy inrush of current will occur, tending to drive it as a motor. If its E.M.F. is much too high it will take too great a proportion of the connected load and blow its fuses

or circuit breakers. When the machine is connected at the same E.M.F. as the line, no current passes from machine to line, nor from line to machine. In order that the dynamo may furnish current, its field rheostat is operated, taking out resistance and raising the voltage of the machine. This is carefully done until the proper proportion of the load is put upon the dynamo.

Especial precaution must be observed to connect similar terminals of the machines, otherwise a short circuit will be pro-

Fig. 38.



duced, the incoming armature acting as a low-resistance path across the bus-bars.

A. The procedure is as follows (see Fig. 38):

A certain number of lamps is being operated from a dynamo and it is desired to connect another one in parallel with it. Ascertain by means of a voltmeter the E.M.F. of the circuit; bring the incoming dynamo up to its rated speed and excite the field so that the same potential as that of the first one is generated. Be careful that the connections which are established are such that when the switches are closed, similar poles of the dynamos are connected.

Close the switches and bring the E.M.F. of the incoming

machine up to the point where the total current divides between the dynamos in proportion to their rated outputs.

To remove a machine from the bus-bars, reduce its field strength until no current is being delivered by the armature to the bus-bars, then open the main switches. Do not open them while current is passing.

B. After the above has been performed a number of times, try the following experiment:

When the machines divide the load equally, alter the field of no. 1 until all of its load is thrown onto no. 2 and then further decrease its field strength until it is seen to be operating as a motor with power from no. 2. This will be indicated by the armature ammeter moving in the opposite direction and an increased reading on no. 2's ammeter. Try the above using no. 1 dynamo in place of no. 2. Explain this fully in the report.

C. Bring the E.M.F. of each machine to 115 volts with no load upon the system, connect them in parallel, and keeping the *speeds* of *each* constant, increase the current in uniform steps until full load for the two machines is reached. Take readings as shown in Table XVII.

Make two sets of readings as follows:

(*a*) Keep E.M.F. of system constant, current equally divided between machines and speeds constant.

READINGS AND RESULTS.

TABLE XVII.

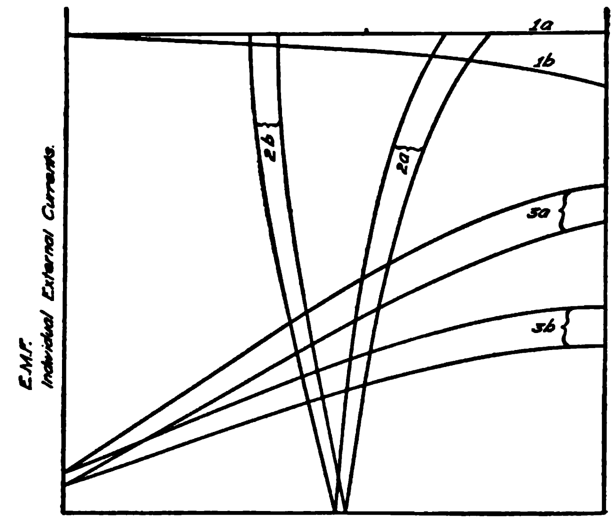
DYNAMO #1						DYNAMO #2						TOTALS	
A	B	C	D	E	F	G	H	I	J	K	L	M	N
E.M.F.	External Current	Field Current	Arm. Current	R.P.M.	Kw. Output	E.M.F.	External Current	Field Current	Arm. Current	R.P.M.	Kw. Output	External Current	Kw. Output
			B+C		A×D				H+I		G×J	B+H	F+L

(*b*) Allow E.M.F. of system to vary, currents not necessarily kept equal but speeds constant.

The first (*a*) brings out the variation of field currents and magnetic characteristics, while the second (*b*) shows the inherent characteristics of the machines when operating in parallel at constant speed.

Report. — Report to contain description of operation with tables of observations and results. Curves to be plotted between: (1) E.M.F. and total current (2); (2) individual external currents

Fig. 39.



and field currents (4); (3) individual external currents and total currents (4) as shown in Fig. 39.

All conclusions and explanations.

Experiment 24. — Operation of Compound Dynamos in Parallel. The operation of compound dynamos in parallel is similar in a general way to that of shunt dynamos. It is essential in power stations and elsewhere to run them in parallel to furnish a large current output for light and power. As the machine differs in its field winding from the shunt dynamo, attention is first drawn to the operation of a single compound dynamo.

The function of a compound dynamo is to maintain at some predetermined point a constant difference of potential. This is accomplished by using a combination of shunt and series field windings, the former furnishing the ampère-turns to bring the dynamo up to its no-load E.M.F. while the latter provides a sufficient number of ampère-turns to compensate for the loss of E.M.F. due to internal drops, armature reaction and line loss. Its regulation is entirely automatic as long as the speed is maintained constant. The E.M.F. of the dynamo will vary with the variation of the current output, rising 10 per cent. or more in railway generators and 3 per cent. or less in lighting machines.

Two compound generators of entirely different characteristics would give unsatisfactory results if operated in parallel. One probable result would be the heavy overloading of one machine due to its taking an undue proportion of the total connected load. The same precaution as to speed, E.M.F. and polarity must be observed in the compound dynamo as in the shunt, with the added precaution as to the sequence of the closing of the switches. This is very important.

The connections of two machines are shown in Fig. 40 and are referred to in the following discussion.

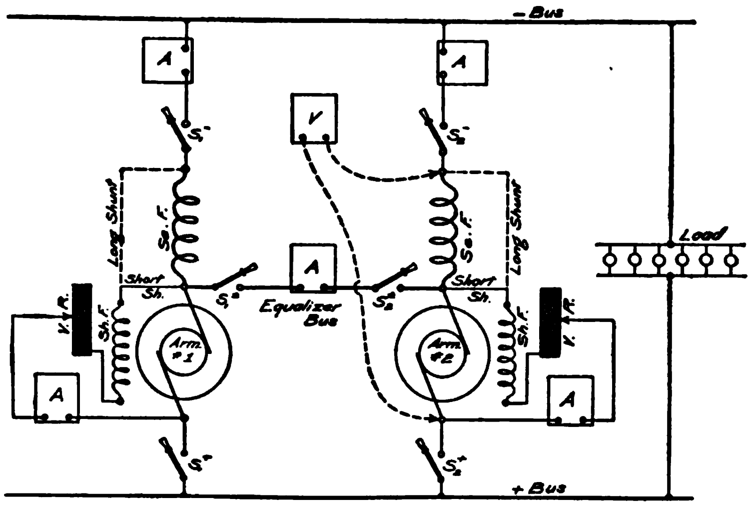
The two compound dynamos are shown ready to connect to the bus-bars and to each other.

If each dynamo is brought up to the proper E.M.F. and S_1^+ and S_1^- are closed, dynamo no. 1 will be operating as a compound dynamo supplying power to the lamps.

If now dynamo no. 2 be brought up to the same E.M.F. and S_2^+ and S_2^- thrown in, no current will be furnished by it, but if the field of no. 2 be made stronger, no. 2's E.M.F. will increase and it will take its proper proportion of the load. However, if the E.M.F. of no. 2 should be so high that it took all of the load and sent current through no. 1's armature and series field in the opposite direction, the series field ampère-turns would weaken the magnetic circuit (as these turns act against the shunt ampère-

turns under this condition.) This would reduce the generated E.M.F. of no. 1, as a result of which still more current would flow into its armature from the line. This differential action is accumulative, resulting in a heavy inrush of current, which operates no. 1 as a motor, causing its armature to try to attain a

Fig. 40.



high speed. The result would be that no. 1's armature and series field would act as a short-circuit path for no. 2, blowing the fuses or opening the circuit breakers.

When two machines are operated as above, they are in unstable equilibrium and any difference in their characteristics will not permit them to be operated together without serious consequences, when the load is a variable one.

In order to avoid this difficulty, which is a characteristic of two series dynamos operating in multiple, there is established between the machines at the point between the armature and the series field what is commonly known as the *equalizer connection.* The switch is known as the equalizer switch and in practice one is placed at each dynamo. The function of this connection can best be seen by reference to Fig. 40.

Assume the same connections as noted before to have been established and S^{*} on each machine closed in the equalizer. The total current furnished by the machine will divide between the series field windings in inverse proportion to their resistances; consequently, if they have the same resistance the current in each will be the same, making the ampère-turns similar. Now if all the other characteristics of the machines are similar, any increase in the load will be taken equally by them.

When the equalizer is closed it is impossible for no. 2 to send current in the opposite direction through series field no. 1, although it is possible for no. 2 to run no. 1's armature as a motor, the current flowing in the equalizer towards no. 2 from S_1^{*} to S_2^{*}.

Procedure to Operate in Parallel.

When load is being carried by one or more machines operating in parallel and an additional one is necessary, it is important to introduce the armature of the incoming machines at the same E.M.F. as the bus-bars. It was formerly customary to use a three-pole switch to connect the machine to the bus-bars, but the sudden inrush of current in the series field of the incoming machine, would cause its E.M.F. to increase rapidly and permit it to assume too much load unless the rheostat in the shunt field were quickly adjusted.

To avoid this danger, three individual switches are now ordinarily employed permitting the series field to be introduced first, thereby exciting the field to the proper value and enabling the E.M.F. of the dynamo to be carefully adjusted by the shunt field rheostat. When the E.M.F. of the armature is correct, the last switch is closed and the E.M.F. of the armature adjusted until the proper load is placed upon the machine.

Referring to Fig. 40, with no. 1 operating, it is desired to connect no. 2 in circuit. S_2^{-} and S_2^{*} are connected. Then the E.M.F. of no. 2 is adjusted to the value of the bus-bars or until there is no difference of potential between the open points of S_2^{+}. S_2^{+} is closed and the E.M.F. of no. 2 is raised until it furnishes the proper current to the circuit.

If the currents do not equally divide between the two machines and further if the magnetic characteristics are not the same for the two machines, the ammeter in the equalizer connection or bus-bar will indicate a flow of current either in one direction or the other.

In order to remove one machine from the circuit, its field current is reduced by means of the shunt rheostat until no current is furnished to the circuit. The ammeter no. 2 will show zero current. Then open switch S_2^+ still having current through the series field. Then open $S_2^{\pm}$ and S_2^- and reduce the shunt field current by means of its rheostat. The motor or engine driving this dynamo can now be stopped and the unit shut down. If S_2^- were opened first dynamo no. 2 would be run as a shunt motor.

Operation of Machines.

A. Operate the machines as indicated in previous paragraphs so as to become accustomed to placing machines in and out of service. Do not open switches with current on. Heed all instructions and take all precautions.

B. After becoming familiar with above operations, run the machines in parallel under the following conditions:

Bring the E.M.F. of each machine to its proper voltage with no load upon it, connect in parallel and then add load by means of lamps or other translating devices until full load for each is obtained. Operate under the three following conditions:

(*a*) Keep E.M.F. of system constant, current equally divided between dynamos and speeds constant.

(*b*) Allow E.M.F. of system to vary, current not necessarily equally divided and speeds variable.

(*c*) Allow E.M.F. of system to vary, current equally divided and speeds constant.

(*a*) would be the case when the machines are exactly similar in all respects. This is not a usual condition.

(*b*) is the normal condition of operation in isolated plants and where attendance is not regular.

(*c*) would be the case of a railway power station.

Report. — Report to contain description of operation of machines in parallel, placing in and taking out of circuit, function of equalizer, connections and tables of observations and results.

Readings and Results.

Table XVIII.

	Dynamo #1						Dynamo #2					Totals	
A	B	C	D	E	F	G	H	I	J	K	L	M	N
E.M.F.	External Current	Field Current	Arm. Current	R.P.M.	Kw. Output	Equalizer Current	External Current	Field Current	Arm. Current	R.P.M.	Kw. Output	External Current	Kw. Output
			B+C		A×D				H+I		G×J	B+H	F+L

Curves to be plotted on same sheet as follows:

(*a*) Three curves between E.M.F. of circuit as ordinates and total current output for abscissas.

(*b*) Four curves between individual current outputs as ordinates and total current for abscissas.

(*c*) Three curves between speeds and total current output.

(*d*) Six curves between field currents for abscissas and individual current outputs for ordinates. All conclusions derived from operation and tests.

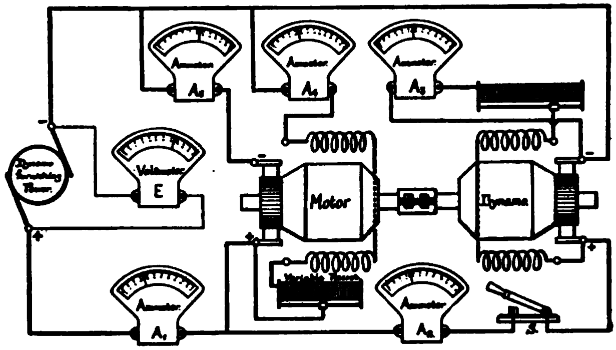
Experiment 25. — Operation of two machines illustrating the "pumping back" method of testing for commercial efficiency and temperature rise. (Kapp's Method.)

The conduct of this test requires the use of two machines of about the same size and capacity, as well as a supply circuit or dynamo of the same voltage as the machines whose efficiencies and temperatures are to be determined.

The great advantages of the test are that there is required only a small amount of power to operate the two machines under full load conditions and great accuracy is secured. For long runs for temperature tests only a small amount of energy is wasted,

though the machines are operated under full load conditions. Heating and sparking troubles may be readily noted.

Fig. 41.



The principle involved is, that the dynamo feeds back power into the circuit supplying the motor, while the power for the combined losses of the two machines is furnished by the circuit or dynamo from which the motor is operating. Consequently if the total losses in the two machines at full load constitute about twenty per cent. of the combined capacities of the machines only the amount of power represented by that percentage will be required from the supply circuit.

The diagrammatic arrangement of the circuits and apparatus is shown in Fig. 41.

The motor and dynamo are mechanically connected either directly or by belt, the former being preferable when the speeds are the same. The motor is operated from a source of power of the same E.M.F. as the dynamo under test, an ammeter A_1 being placed in the supply circuit. A_4 will give the current in the motor field while A_5 will show the current in the armature. When the dynamo is entirely disconnected from the motor, the ammeter reading will equal the sum of the readings on motor ammeters A_4 and A_5. The voltmeter E, will show the E.M.F. of the supply circuit, while the product of the readings of E and A_1 will equal the power necessary to operate the motor at its proper speed under no load conditions.

The dynamo may now be mechanically connected to the motor and its E.M.F. made equal to the E.M.F. of the supply circuit. Its polarity should be similar in direction to the latter. When no difference of potential exists between the open points of the switch S, it can be closed. No current will pass from the dynamo to line or *vice versa.* Increase the field strength of the dynamo to such an extent that the full load current of the dynamo flows through the motor and dynamo armatures. This current will be shown by ammeter A_2, while A_5 will indicate the dynamo field and armature currents plus the motor armature current, and A_1 will read only the armature and field currents of the motor which represent the total losses in the two machines and the cables or wires connecting them. The machines can now be operated under full load or overload conditions for such length of time as is necessary to raise the dynamo to its maximum temperature.

The dynamo sends through the low resistance circuit of the motor and dynamo armatures a current proportional to the increase in generated dynamo E.M.F. over the E.M.F. of the motor. The current will be

$$I = \frac{E_d - e_m}{R_a^d + R_c + R_a^m}$$

Where E_d = E.M.F. generated in dynamo armature.
e_m = Counter E.M.F. of the motor armature.
R_a^d = Resistance of dynamo armature.
R_c = Resistance of connections.
R_a^m = Resistance of motor armature.

To determine the efficiency of the dynamo, it becomes necessary to use the motor as a *calibrated dynamometer.* Its losses are determined by the Stray Power Method at various points from no load to full load and its armature and field resistances are carefully ascertained.

Then the dynamo may be mechanically connected to the motor and the power required for (1) friction measured. This will be shown by the increase in the A_1 ammeter reading. Then (2) the field of the dynamo can be separately excited so that the E.M.F.

of the dynamo has different values. The increase in the reading of A_1 will be the measure of the core losses in the dynamo armature.

Now the dynamo may be connected to the line circuit, and about 10 values of the current outputs secured by adjusting the dynamo field rheostat. At each step readings should be made of all ammeters, voltmeters and speeds. The efficiency of the dynamo can be expressed by the equation:

$$\text{per cent.} = \frac{A_2E}{A_2E + (A_1E - \text{all motor losses})}$$

A typical calculation is herewith shown:

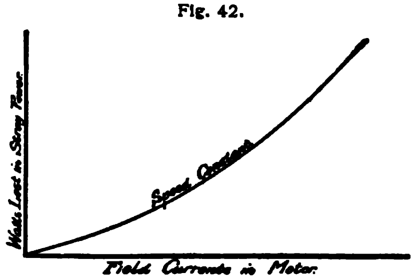
$$\text{per cent.} = \frac{54 \times 113}{113 \times 54 + (23 \times 113 - 13 \times 113)}$$

$$\text{per cent.} = \frac{6102}{6102 + (2599 - 1469)} = \frac{6102}{7232} = 84.3 \text{ per cent.}$$

Operation.—(*a*) Determine carefully all resistances of dynamo and motor.

(*b*) Make connections as shown in Fig. 41, and take readings of all instruments at ten points from no load to full load. Keep speed of dynamo constant at its rated value by adjusting the

Fig. 42.



motor field strength. (*c*) Then make a careful stray power loss test of the motor and tabulate results.

(*d*) Operate dynamo from motor to determine friction loss.

(*e*) Separately excite dynamo field with currents corresponding to those used in (*b*) and measure core losses.

(*f*) A detailed temperature run can be made upon the machines.

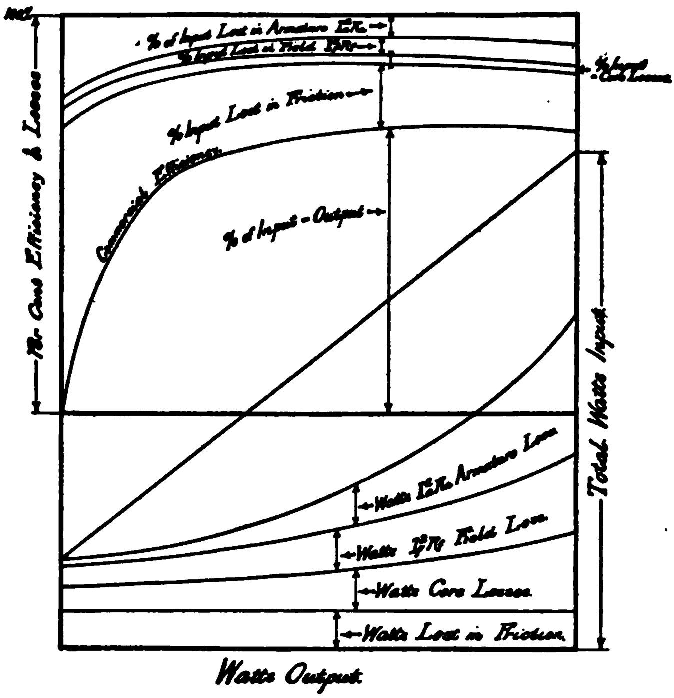
Report. — Plot all results in form of curves.

(*a*) From results of *b*, *c*, *d* and *e* calculate efficiency of dynamo at various parts of full load.

(*b*) Stray power loss test (Fig. 42) and efficiency test of motor on one sheet. (Fig. 30.)

(*c*) Efficiency and loss curves for dynamo on one sheet. (Fig. 43.)

Fig. 43.



(*d*) Readings and results arranged as in Table XIX. All measurements.

Discussion and conclusions.

TABLE XIX.

Line		Motor										Dynamo	
A	B	C	D	E	F	G	H	I	J	K	L	M	N
E.M.F.	Current A_1	Current in Armature A_2	Current in Field A_4	Total Current	Watts Input	Watts Lost in Armature	Watts Lost in Field	Stray Power Loss	Total Losses	Watts Output	% Efficiency	Current to Motor A_5	Current in Field A_6
				$C+D$	$A \times E$	$C^2 \times R_a$	$D^2 \times R_f$		$G+H+I$	$F-J$	$K/F \times 100$		

Dynamo													
O	P	Q	R	S	T	U	V	W	X	Y	Z	A′	B′
Total Current	Watts Input	Watts Lost in Armature	Watts Lost in Field	Friction and Windage Loss	Core Loss	Total Loss	Watts Output	% Efficiency	% of Input Lost in Armature	% of Input Lost in Field	% of Input Lost in Core	% of Input Lost in Friction & Windage	Total % -100
$M+N$	K	$O^2 \times R_a$	$A \times N$					$V/P \times 100$	$Q/P \times 100$	$R/P \times 100$	$T/P \times 100$	$S/P \times 100$	$W+X+Y+Z+A'$

Experiment 26. — Operation of a Constant Current Arc Dynamo and the Operation and Study of Arc Lamps.

The constant current arc dynamo used in this experiment is the Thomson-Houston machine and is intended to operate series arc and incandescent lamps. It delivers a constant current of 10 ampères with a variable potential, the value of this potential depending on the number of lamps connected to the machine.

The armature is of the "open coil" type, there being three sections or windings, one end of each coil being connected to a common point at the pulley end of the machine, while the other ends of these coils are connected to the three sections of the three-part commutator. The armature is spherical in shape and revolves between two cup-shaped pole pieces which nearly enclose it. The field magnets consist of two cylindrical cast-iron cores with wrought-iron bars holding them in place, these bars also forming part of the magnetic circuit.

Bearing on the commutator are four brushes, two to a set, these brushes being carried by a movable set of arms or levers, by the movement of which the regulation is accomplished. The operation of this regulating mechanism should be carefully noted when running the machine. In large machines of this type there is provided an air blower, the function of which is to provide a blast of air at the right instant to blow out the spark which occurs when the leading brush leaves a commutator bar.

There is placed upon the wall a regulator which controls the movement of the brush shifting apparatus. This consists of a pair of solenoids in series with the main circuit, which act on a pair of iron cores, lifting them when the current becomes greater than that for which it is set; this action opens the shunt circuit *A*, in Fig. 44, and forces the whole current to pass around the electromagnet *M*, which controls the movement of the brushes. This magnet operates a lever which moves the brushes about the commutator, thereby causing the current to assume its proper value.

The action of the machine is stopped by short-circuiting the

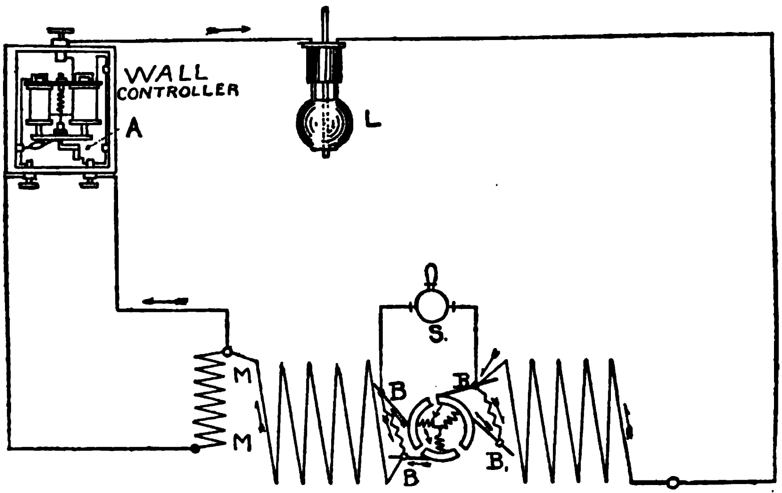
armature by means of the switch *S*, placed on the frame of the machine. This prevents the current from passing through the field magnets and external circuit, and therefore stops the machine from exciting its field.

By studying carefully the internal connections of the armature, it will be seen that when one of the coils is connected to one set of brushes the other two coils are connected in parallel with each other and to the other set of brushes but in series with the first coil. When the maximum potential is required, the individual brushes of each set are shifted so as to be as close as possible to each other, while when the minimum potential is necessary these brushes are wide apart. Other types of machines for the same purpose as the Thomson-Houston dynamo, operate similarly, the potential being regulated by electro-mechanical devices.

(For a detailed description of this machine, reference can be made to a special hand-book relating to it or to Thompson's "Dynamo Electric Machinery.")

Connections of the machine are shown in Fig. 44.

Fig. 44.



Switchboard. — The arc lighting switchboard consists of two

panels of slate supported in an iron frame, and carrying metal contact strips. In the front face of the outer panel are a number of rows of rubber bushings through which are passed brass connection plugs, these serving as the means for connecting the dynamo to the various lamp circuits.

All of the bushings of the same horizontal row to the *right* of the center of the panel are electrically connected, except those of the bottom row, and similar connection is made between the bushings to the *left* of the center. A brass strip is supported on the rear panel behind each vertical row of holes, and is furnished with bushings corresponding with those in the front rows. These strips can be put into electrical connection with any one of the horizontal conductors it crosses by the use of the brass plugs mentioned above.

In a standard panel the number of rows of holes arranged horizontally is equal to one more than the number of generators. The vertical rows are always twice the number of generators. The *positive* leads of the machine are attached to the binding posts on the *left* hand end of the horizontal conductors; the *negative* leads being connected to the corresponding binding posts at the *right* hand end of the board. The *positive* line wires are connected to the vertical straps on the *left*, and the *negative* wires to similar straps on the *right* of the center of the panel.

The holes of the lower horizontal row have bushings connected to the vertical straps only. Plugs, joined in pairs by flexible cable and inserted in the proper holes, serve to connect together any of these vertical straps as needed; normally independent circuits being thus interconnected when one generator is of sufficient capacity to supply these several circuits.

Operation.—Insert an ammeter and connect lamps to the proper terminals of the switchboard. Start the machine and manipulate the switchboard so as to illustrate the operation of entirely independent circuits. *Under no circumstances open the circuit of an arc dynamo.* Short-circuit the apparatus you desire

to cut out and then remove it from the circuit. *Do not open any switchboard connection.*

Note the regulation of the machine when the number of lamps in circuit is changed and describe the operation of the machine. Note any peculiarities which attract attention.

Study of an Arc Lamp. — If two pieces of carbon are connected by wires to a proper dynamo, brought in contact and then separated a short distance, the current will continue to flow across the gap, producing the brilliant light known as the electric arc. When the arc is produced in air the carbon rods are consumed by the oxygen of the air. The positive carbon assumes a cup shape at the end, while the negative assumes a pointed form, in the case of a direct-current open arc. About 40–50 volts are required to maintain a good steady arc and the usual current is from 6 to 10 ampères. Larger arcs are used in lighthouse service and for searchlights, these sometimes taking as much as several hundred ampères.

In ten ampère arcs the positive carbon is consumed at the rate of about one inch per hour, in the open air, while the negative carbon is consumed at about half this rate.

In commercial lamps the mechanism is arranged to "strike" the arc by causing the carbons to touch and then separate them to the requisite distance to maintain a proper arc; the mechanism then feeds the carbons into the arc at the rate at which they are consumed. The mechanism should also cause the points to recede automatically in case the arc becomes too short; it should also bring the carbons together for an instant to strike the arc again in case the flame for any reason should go out.

In the "clutch lamps," a clutch is employed to pick up the upper carbon holder, the lower carbon remaining fixed. The clutch is worked by an electromagnet or a number of magnets, through which the current passes. If the lamp goes out the magnet releases the clutch, the upper carbon falls by its own weight and touches the lower carbon, the current is reëstablished, and the electromagnet causes the clutch to grip the

carbon holder and lift it, thereby striking a new arc. If the arc grows too long the increased attraction of the magnet causes the clutch to slightly release its hold on the upper carbon holder, permits it to drop slightly and thus shortens the arc to its proper length.

Method for Dynamo. — Connect the machine for operation and place in the circuit an ammeter and across the machine terminals a voltmeter. Vary the load from no load to the full load by means of arc lamps and series incandescent lamps. Note the corresponding values of E.M.F., current and speeds. Note position of regulating mechanism and brushes.

Method for Lamps. — Connect an ammeter in circuit and a voltmeter across the lamp terminals. Note and record the variations in these quantities with different lengths of arc and measure the E.M.F. across the arc. Note the direction in which the light is thrown when the direction of current in the arc lamp is reversed.

Report. — All results. Diagram of connections of dynamo and circuits. Diagram of lamp connections. Explanation of operation of machine and conclusions.

READINGS.

TABLE XX.

Readings on Machine.				Readings on Arc Lamps		
Total Volts.	Amperes	No. of Arc Lamps.	No. of Incand. Lamps.	Volts.	Amperes	Length of Arc. (Inches)
		1.				1/8
		2.				1/4
		3.				3/8
			1.			1/2
			2.			5/8
			3.			3/4.

PART II.

Alternating Current Tests.

Useful Equations.

$$I = \frac{E}{Z},$$

I and E denote the effective values of current and E.M.F.,

$$\frac{\text{Effective value of sine}}{\text{Maximum value of sine}} = \frac{1}{\sqrt{2}},$$

$$\frac{\text{Average value of sine}}{\text{Maximum value of sine}} = \frac{2}{\pi},$$

$$Z = \sqrt{R^2 + X^2}.$$

In general, if both inductance and capacity are in circuit

$$X = \omega L - \frac{1}{\omega C},$$

where $\omega = 2\pi f$.

$$f = \frac{p \times N}{60},$$

$$P = EI \cos\theta = I^2R.$$

In a three-phase circuit

$$P = \sqrt{3}\, EI \cos\theta$$

$$\tan\theta = \frac{X}{R}, \quad \sin\theta = \frac{X}{Z}, \quad \cos\theta = \frac{R}{Z}.$$

Resistance drop $= IR$,
Reactance " $= IX$,
Impedance " $= IZ$.

$$\mathbf{B} = \frac{.4\pi n I}{\frac{l}{\mu}},$$

where n = number of magnetizing turns, and
l = length of magnetic circuit.

$$\mathbf{L} = \frac{.4\pi n^2}{\frac{l}{s\mu}}, \text{ where } s = \text{cross section of the coil,}$$

$$\mathbf{M} = \text{mutual inductance of two coils} = \frac{.4\pi n_1 n_2}{\frac{l}{s\mu}}.$$

The maximum value of the induction in a transformer is given by the equation,

$$\Phi_{max} = \frac{E \times 10^8}{\sqrt{2}\pi \times n \times f \times s},$$

where E = effective open circuit secondary E.M.F.

This equation is only true when Φ is a sine function.

At any instant,

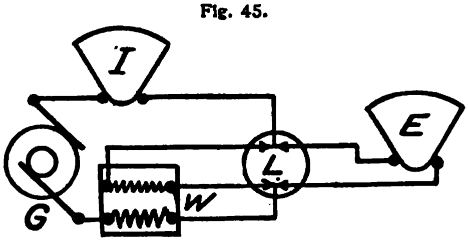
$$\Phi = \frac{\mathbf{R}}{\mathbf{F}}, \text{ where } \mathbf{F} = \text{the resultant M.M.F.}$$

Elementary Properties of A. C. Circuits.

Experiment 1.—Measurement of an Inductance by the Method of Impedance.

In order to determine the inductance of the coil L, the drop of potential in the coil is measured at a known current and frequency. This drop is due both to resistance and inductance, hence in order to find the inductance it is necessary to have already determined the resistance. The drop across the coil is

Fig. 45.



$$E = I\sqrt{X^2 + R_0^2}.$$

If the coil contains no iron its losses are due only to the ohmic resistance, which may be determined by the direct current method. But if the coil has an iron core, hysteresis and eddy current losses result. All these losses may be considered as due to the current in the coil flowing through a resistance of such a value as to cause the energy loss in question. This hypothetical resistance is called the effective resistance of the coil and is found by dividing the wattmeter reading of the energy absorbed by the coil by the square of the corresponding current, or

$$W_0 = I^2R_0, \quad R_0 = \frac{W_0}{I^2}.$$

R_0 will vary with the frequency and current value, hence must be determined for each condition. If the coil has no iron its effective resistance is the same as the ohmic resistance. In this case the voltmeter can be omitted and R_0 determined by the direct current method.

Method. — Make connections as shown in Fig. 45 and note values of current, speed, watts and voltage across the coil. The value of **L** may be obtained from the equation

$$\mathbf{L} = \frac{\sqrt{E^2 - R_0^2 I^2}}{I\omega}$$

in which E is the drop across the coil. If R_0 is not known, its value must be determined as already explained.

Report.— Evaluate **L** from several sets of simultaneous readings at different values of ω and I; give the values of the different quantities in the equation.

Experiment 2. — Measurement of a Condensance.

The drop across a condensance is

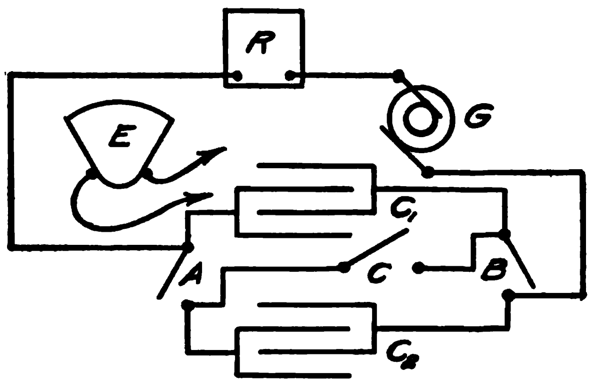
$$E_1 = \frac{1}{\omega C} \times I = \frac{E_2}{R} \times \frac{1}{\omega C},$$

where E_2 is the drop across the known resistance R, which is in

series with the capacity C. R must be sufficiently great to produce a convenient deflection of the voltmeter.

Method. — Make connections as shown in Fig. 46. A, B and C are single throw, single pole switches. To read drop across C_1

Fig. 46.



close B with A and C open. To read drop across C_2, close A, leaving B and C open. To read drop across C_1 and C_2 in series, close C, leave A and B open. To read drop across C_1 and C_2 in parallel, close A and B, and leave C open. Take drop across R for each drop across condensers. Determine separate capacities of C_1 and C_2 also capacity in series and parallel.

Taking drop across C_1 alone, vary frequency 25 per cent. either side of its rated value and take five readings, one at rated frequency, and two either side. Determine capacity by equation

$$C = \frac{E_2}{E_1 R \omega}.$$

For a strictly accurate measurement an electrostatic voltmeter should be used. Unless the condenser is very large, the current taken by an electromagnetic voltmeter, probably a few hundredths of an ampere, will introduce a considerable error; it is difficult to correct for this error, as the inductance of the voltmeter resonates to some extent with the capacity of the condenser.

Report. — Tabulate readings obtained. Calculate capacity for all combinations employed. Explain reason for difference in value of total capacity for series and parallel arrangements.

Experiment 3.—Measurement of Power with Inductive Load.

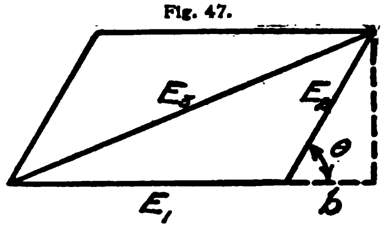
(*a*) Three voltmeter method.

(*b*) Three ammeter method.

(*c*) Wattmeter method.

(*a*) and (*c*):—If the non-inductive resistance R is known, it is possible to find the power developed in the coil L by determining the drop across R, then across L, and finally across both R and L. Owing to the difference in phase between these E.M.F's the drop across R and L in series will not be equal to the sum of the drops across R and L individually.

Fig. 47.



The E.M.F's may be represented vectorially as in Fig. 47.

The watts developed in the coil may be deduced from this diagram.

$$P = E_2 I \cos\theta = \frac{E_2 E_1}{R}\cos\theta,$$

$$\cos\theta = \frac{b}{E_2},$$

$$b = \frac{E_3^2 - E_2^2 - E_1^2}{2E_1},$$

and therefore

$$\cos\theta = \frac{E_3^2 - E_2^2 - E_1^2}{2E_1E_2}.$$

Hence

$$P = \frac{E_3^2 - (E_2^2 + E_1^2)}{2R}.$$

Method.—Note the three indicated voltmeter readings, as shown in Fig. 48, and deduce the value of P. Note the reading of the wattmeter in order to compare it with the value obtained by calculation.

Fig. 48.

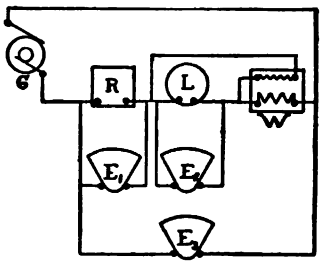
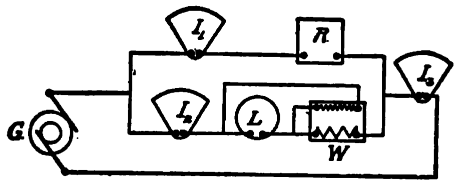


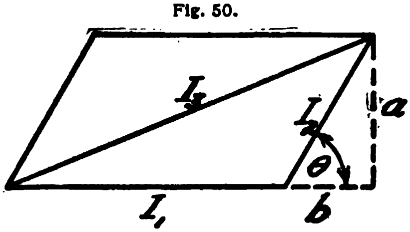
Fig. 49.



Take several sets of readings of the voltmeters under different conditions. If three voltmeters are not available, all the readings may be obtained with one voltmeter by changing the terminals from one place to another, provided the speed and impressed voltage are kept constant. R should be chosen so as to make the two drops IR and $I\omega L$ as nearly equal as possible. That is the condition of greatest accuracy.

Report.—Tabulate the readings obtained, deduce the corresponding values of P, and calculate the average value.

Fig. 50.



(*b*):—The watts P developed in the coil L may be found from the readings of three ammeters connected as in Fig. 49. Owing to differences of phase the effective value of the current I_3 is not equal to the arithmetical sum, but to the vectorial sum or resultant of I_1 and I_2.

The readings of the three ammeters may be represented vectorially as in Fig. 50. From this construction the value of P may be deduced.

$$P = I_1 R \times I_2 \cos\theta,$$

$$\cos\theta = \frac{b}{I_2}, \qquad a^2 + b^2 = I_2^2,$$

$$I_3^2 = I_2^2 + 2bI_1 + I_1^2,$$

$$b = \frac{I_3^2 - I_2^2 - I_1^2}{2I_1},$$

$$P = \frac{R}{2}\left[I_3^2 - (I_2^2 + I_1^2)\right].$$

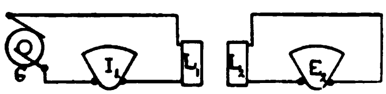
Method. — Connect as shown in Fig. 49. The three ammeter readings should be taken simultaneously. The known ohmic resistance R should have such a value as to make the two ammeter readings $I_1 + I_2$ as nearly equal as possible. Note the reading of the wattmeter, in order to compare it with the calculated value of the watts. Take several sets of readings under different conditions.

Report. — Tabulate the readings obtained, calculate the values of P, and find the average value.

Experiment 4. — Measurement of the Mutual Inductance of two Coils, Using Successively Both Coils as the Secondary.

When an alternating current passes through a coil, an alternating magnetic field is produced in the surrounding space. An E.M.F. will be set up by these lines of force in any neighboring coil. This E.M.F. depends on the primary current, on the frequency, and on the mutual inductance of the coils. It is given by the equation

Fig. 51.



$$E_2 = \omega \mathbf{M} I.$$

Method. — Fig. 51 shows the necessary connections. Note the frequency and the instrument readings. After this, interchange the connections so as to make L_1 the secondary, and L_2 the primary, and take a second set of readings. The resulting value of $\mathbf{M}$ should be the same in both cases. This will only be true if the relative position of the coils has not been altered when

changing the connections, and when there is no iron in the construction. In an iron core the variation of the permeability with the induction causes a corresponding change in **L** and **M** ; so that in measuring these quantities in the case of coils wound on iron cores, especially with closed magnetic circuits, it is necessary to state the flux density or the magnetomotive force per inch of length corresponding to each determination.

Report. — Tabulate the readings and deduce the values of **M**.

The Alternating Current Generator.

Discussion of its Distinctive Features.

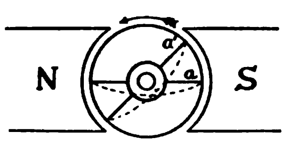
The action of the machine is the same as that of a separately excited D. C. dynamo, except for certain peculiarities due to the difference in the nature of the armature current. The fact that this current is alternating affects both the armature reaction and the internal drop in voltage.

(*a*) *Armature Reaction.*

It is pulsating in single phase, but constant in polyphase machines. It depends on the phase as well as the amplitude of the current.

In Fig. 52 the current in the coil *a* will be a maximum when in the position shown, provided that it is in phase with the E.M.F. This is because the E.M.F. is always a maximum where $d\mathbf{B}/dt$ is greatest, independently of the phase of the current. Neglecting field distortion, this will always be when the coil is in the position *a*.

Fig. 52.



With non-inductive load, therefore, both current and E.M.F. are a maximum when the coil is at *a*. The effect on the field will be to produce distortion, but no direct demagnetization. There are no back ampère turns because there is no commutator.

If the current lags behind the E.M.F. it will not reach a maximum until the current has reached some position *a'*, depending on the angle of lag. The current will then have a direct demag-

netizing action on the field in addition to the distorting effect which is less than at non-inductive load.

In a similar way it will be seen that a leading current tends to strengthen the field due to the magnet windings.

The divergence between the lines *a* and *a'* is the angle of lag between the current and the induced electromotive force on open circuit; it is evident therefore that the distorting effect on the field due to the current will be approximately proportional to the cosine of this angle of lag, while the directly demagnetizing effect will depend similarly on the sine.

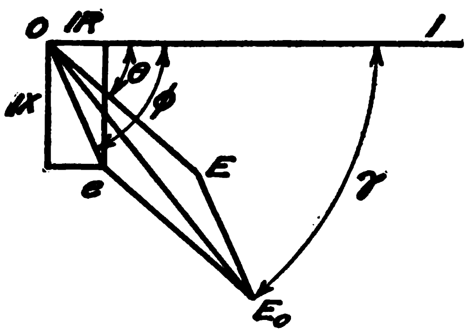
The effect of the armature current on the flux distribution is to superpose on the no load flux a hypothetical flux in phase with and proportional to the armature current; the effect on the diagram of voltages is to introduce a hypothetical component of E.M.F. proportional to the rate of change of the hypothetical flux and therefore in quadrature with the current.

(*b*) *Armature Drop.*

In a D. C. machine, this is due only to commutation losses and ohmic resistance, but in an alternator the varying current

Fig. 53.

Inductive load.

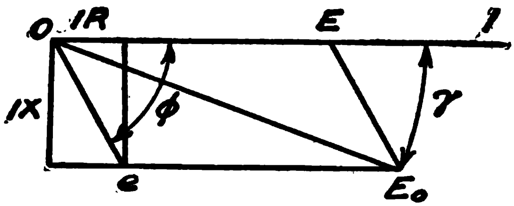


produces a stray flux which cuts the armature conductors, producing a counter E.M.F. of self induction.

Figs. 53 and 54 show how it comes about that the diminution in volts due to this counter E.M.F. is greater with an inductive than with a non-inductive load.

Fig. 54.

Non-inductive load.



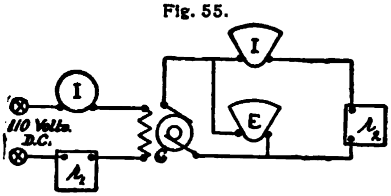
In these diagrams, $\overline{OE}$ and $\overline{OE_0}$ represent the terminal volts and induced volts respectively. $\overline{Oe}$ is the E.M.F. consumed by the internal impedance of the armature. Whatever the angle θ, $\overline{OE_0}$ must be the resultant of $\overline{Oe}$ and $\overline{OE}$. Therefore, as θ increases the terminal volts decrease more and more as the line $\overline{Oe}$ comes into phase with $\overline{OE}$.

This action occurs not only in alternators, but also in many other cases, as in transformers and transmission lines.

Experiment 5.—Field Compounding.

As the load increases, the terminal volts of an A. C. dynamo are diminished on account of the actions described above. The object of this test is to determine at various loads what increase of excitation is necessary to maintain the no-load terminal voltage.

Fig. 55.



Method.—Fig. 55 shows the connections for the test. Run the A. C. generator at constant frequency and constant terminal voltage, varying the load from zero to 50 per cent. over-load. Note the field and armature currents. Take six readings. The load must be non-inductive.

N.B. — Keep frequency and terminal volts constant.

Report. — Plot a curve with field current as ordinate, and armature current as abscissa. Tabulate readings as shown in the following table.

Field Amperes.	Armature Amperes.	Armature Volts.	Speed.	Remarks.

Experiment 6. — Full-load Saturation Curve, or Magnetization Curve at Full-load Current.

In this test it is designed to show the relation between the excitation and the resulting terminal volts, when the armature is delivering its rated current output.

Method. — The connections are the same as those of Fig. 55. The resistance r_2, however, must be such as to carry full-load current throughout a wide range of resistance. The current must be kept constant by adjusting r_2 as the terminal volts increase. Make at least ten observations of the terminal volts and field current, with ascending E.M.F., and the same number descending.

In determining a magnetization curve great care must be taken to change the field current continuously in the same sense, and if, for instance, it is desired to check a previous reading on the ascending curve, the field current must be brought up to the desired value, starting from zero. If this precaution is not observed, the points determined will not lie on the curve on account of the effect of hysteresis.

The tabulation of readings should be the same as in Experiment 5.

N. B.—Keep the frequency and the armature current constant.

Report. — Construct a curve between terminal volts as ordinates, and field amperes as abscissæ.

Experiment 7. — No-load Saturation Curve, or Magnetization Curve at No-load.

The voltmeter readings of Experiment 6 will be lower than the terminal volts at no load owing to impedance drop. It will be possible to determine the exact amount of this reduction by determining a magnetization curve with open armature circuit, and comparing it with the curve of Experiment 6. In practice it is customary to carry on this test at the same time as the core loss determination, which is explained under Experiment 8.

Method. — Make connections as in Fig. 56, Experiment 8. With the armature circuit of the alternator open, take six readings of alternator terminal voltage between zero and one-fifth of the rated value. These readings are to be used in connection with Experiment 9. Take eight readings of voltage from one-fifth rated value to 1.2 times rated value for successive ascending and descending values of the alternator field current.

N. B. — Keep the frequency constant at its rated value.

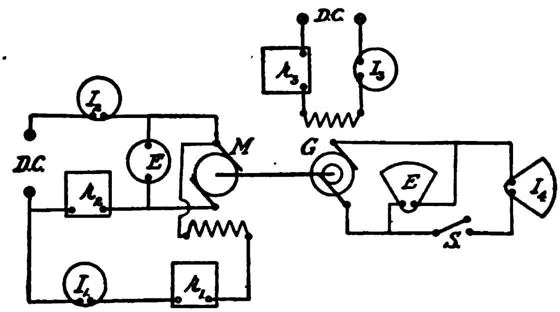
Report. — Tabulate the readings. Plot no load magnetization curve on the same sheet and to the same scale as the curve of Experiment 6. Plot a curve for the first six readings on a separate sheet to an enlarged scale. Use terminal volts for ordinates and field currents for abscissæ in both instances.

Experiment 8. — (a) Short-Circuit Core Loss. (b) Open-Circuit Core Loss.

(*a*) The core loss in an alternator is made up of the eddy current and hysteresis losses. These latter vary considerably with the load because the armature current produces a magnetic field which modifies the flux densities and increases the losses. This increase is called the load loss, and it is usually determined by finding the core loss at short circuit. The conditions are not then quite the same as when the machine is operated at its rated voltage and non-inductive load on account of the differences in power factor and flux densities. It is therefore customary to assume that the load losses are equal to one third of the short circuit core losses at the current in question.

Method. — The usual method of measuring the core losses is by noting the difference in the power taken by the driving motor when the alternator field is open and closed.

Fig. 56.



During the test the field current of the driving motor must be kept constant at its rated value in order that the losses of this motor may be readily subtracted from the total power input; for the same reason it is very desirable that the motor should have copper brushes. The motor should also be no larger than necessary. The speed must be kept constant throughout the test, and this is accomplished by adjusting the voltage supplied to the motor armature, either by means of a resistance directly in the circuit, or by boosting the direct current line voltage.

The required connections and instruments are shown in Fig. 56. The armature of the alternator G is short-circuited through an ammeter. Run the motor disconnected from the alternator at rated alternator speed, and with normal field.

Then $$W = EI_2 - I_2^2R_m.$$

Now couple the motor and alternator together, the latter having its armature and field circuits open.

The friction loss of the alternator may then be obtained from the instrument readings by the equation

$$P = E'I_2' - W - I_2'^2R_m.$$

Short circuit the armature upon itself by closing switch s, and

apply a small value of field excitation; the short circuit core loss of the alternator is then

$$P_1 = E''I_2'' - W - P - I_2''^2R_m - I_4^2R_a.$$

In a similar manner, by increasing the field excitation of the alternator, successively larger short circuit core loss values may be obtained corresponding to higher values of alternator armature current.

The object of determining the short circuit core loss is that it furnishes a good indication of the load losses which occur in an alternator armature when in normal operation. These are due to flux variations produced by the armature M.M.F., and which occasion local hysteresis and eddy current losses. It is found that these load losses are greater for a given armature current when the machine is operated at short circuit than under conditions of normal load at unity power factor; it is therefore customary to assume that the load losses of an alternator at any armature current and unity power factor are equal to one-third of the short circuit core loss determined at the same armature current value. In calculating the efficiency of the machine, the load losses obtained in this way are added to the open circuit core loss plus the various other losses.

The stray power loss W of the motor and the friction P of the alternator are constant throughout the test. The copper losses in the armatures of the motor and alternator, on the other hand, vary with each value of the field.

Report. — Plot a curve between core loss in watts and alternator armature current as abscissæ. Calculate the load losses at unity power factor by taking one third of such load losses, as actually determined at short circuit.

Care must be taken to begin with a small value of field current in order to avoid burning out the armature. Increase the field current till the armature current is carried up to 50 per cent. overload. It will take from 15 to 35 per cent. of normal field current to give full load armature current, depending upon the design of the machine.

N. B. — The frequency and motor field current must be the same for every reading. Take six readings.

Let W = stray power loss of motor; this is constant since field current and speed are constant.

R_a = resistance of armature of alternator.

R_m = " " " " motor.

I_1 = current in field of motor, constant.

I_2 = " " armature of motor.

I_3 = " " field of alternator.

I_4 = " " armature of alternator.

E = voltage across armature of motor.

(*b*) The open circuit core loss is determined by the method just described except that, the switch S being open, the alternator armature is on open circuit, and I_4 is zero in the above equation.

Experiment 7, the determination of the no-load saturation curve, is always carried on at the same time as the determination of open circuit core losses. The only change in connections required is to place a voltmeter across the terminals of the alternator. Readings are then taken with ascending and descending voltage as described under Experiment 7.

D.C. Motor.			Alternator.				Remarks.
Field Amperes	Armature Amps.	Arm. Volts.	Field Amps.	Armat. Amps. [Part (a)]	Armat. Volts. [Part (b)]	Speed.	

N. B. — The frequency and motor field current must be kept constant throughout.

Report. — Plot a curve with core loss in watts as ordinate, and alternator field current as abscissa. Draw this curve on the same sheet of cross-section paper, and to the same scale, as the corresponding curve of (*a*).

Experiment 9. — Determination of Synchronous Impedance.

When an alternator is supplying a current, the armature reaction as well as the resistance of the winding combine to cause a drop in terminal volts. In polyphase machines the principal effect of the armature current is to develop a radial magnetomotive force which remains constant for any given current and fixed in space, except that its angular position is dependent on the power factor. The fluctuating stray field caused by the current in the armature conductors furthermore develops a counter E.M.F. of self-induction due to magnetic variations which are synchronous with the rotation of the machine. Both of these agencies affect the terminal voltage in a similar manner, producing a change in it directly proportional to the current. Since the resistance drop is also proportional to the current, it is convenient to regard the total voltage change as being equal to a constant called the "synchronous impedance" multiplied by the current. In this constant are included the synchronous reactance, which refers to the electromagnetic reactions per ampere, and the effective resistance, which represents the energy components and includes both the true ohmic resistance and the apparent resistance due to load losses.

Upon the value of synchronous impedance depends the regulation of an alternator. Considered vectorily, the line E.M.F. equals the induced E.M.F. of the generator minus the impedance E.M.F. IZ; referring to Fig. 54 if

$$\tan^{-1} \phi = \frac{IX}{IR}$$

is large, the regulation will be poor, if small the regulation will be good. In the design of an alternator the value of synchronous impendance admissible would depend upon the nature of the load which the generator was required to carry, if with a given value of synchronous impedance the load was made up wholly of lamps or purely non-inductive, the generator would regulate for constant potential much better than it would when carrying an inductive load; Figs. 53 and 54 show this effect very clearly. If generators are designed to be operated in parallel, the value of

synchronous impedance in each machine must be such as to keep the short circuit current down to a safe limit.

At short circuit, the terminal volts are zero, and the impedance drop IZ consumes the entire induced E.M.F. That is, in Fig. 53 the terminal voltage $\overline{OE}$ is zero and $\overline{OE_0}$ consequently must become equal to the synchronous impedance E.M.F. Oe. Therefore, at short circuit,

$$\overline{OE_0} = IZ,$$

in which equation I is obtained from the ammeter reading, and $\overline{OE_0}$ is given by opening the circuit without changing the field-current, and noting the voltmeter reading. All the quantities necessary for determining Z may be taken from Experiments 7 and 8.

Another method of finding the synchronous impedance is to run the alternator as a synchronous motor. (See Exp. 13.) The field excitations are adjusted so as to make the machine under test draw a heavy leading current from the line; the vector $\overline{OE_1}$ then becomes almost vertical, while vector $\overline{OE_3}$ increases without, however, changing its direction. When the angle of lead of the current is made to approach 90° the lozenge-shaped diagram of voltages $OE_1E_3E_2$, Fig. 58, becomes greatly flattened out, so that the synchronous impedance drop,

$$\overline{OE_3} = IZ,$$

is only slightly out of phase with the terminal volts $\overline{OE_1}$ and the induced volts $\overline{OE_2}$; it may therefore be obtained directly, with slight error, by subtracting the former voltage from the latter.

The readings required for the determination of Z by this second method may be taken from Experiments 7 and 13.

Experiment 10. — External Characteristic Curve. Non-Inductive Load.

This is the relation between the terminal volts and the armature current with non-inductive load.

Method. — Run the alternator at its rated speed and no-load voltage. Keeping the field current constant, close the armature

circuit, and note the terminal volts at increasing values of the armature current. Carry the test up to 50 per cent. overload. The tabulation of the readings should be the same as in experiment 5.

N. B. — Keep the field current and frequency constant.

Report. — Plot a curve with terminal volts as ordinates and armature current as abscissa. This curve should be drawn on the same sheet, and to the same scale, as the curves (*a*) and (*b*) of Experiment 11. All three curves should start from the same no-load voltage.

Synchronous Machines in Parallel.

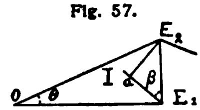
Discussion of the Necessary Conditions.

In synchronizing alternators, there are four conditions which the E.M.F. of the machines must fulfill. They are

1. Equality of amplitude.
2. " " phase.
3. " " frequency.
4. Coincidence of wave shape.

If any one of these conditions is unfulfilled, a wattless current flows from one machine to the other. They then oscillate in speed with respect to each other, and may drop out of step.

Fig. 57.



In Fig. 57 $\overline{OE_1}$ and $\overline{OE_2}$ represent the induced E.M.F.'s of two alternators connected in multiple. Since there is a difference in phase θ, the resultant E.M.F. acting through the circuit formed by the armatures of the two machines is $\overline{E_1E_2}$. The current produced may be represented by the line $\overline{E_1I}$. $\overline{E_1a}$ is then the ohmic drop, and $\overline{E_2a}$ that due to inductance.

As the machines rotate synchronously without any rigid mechanical connection they have a tendency to oscillate in space with respect to each other. The angle θ will vary periodically.

The natural period of this oscillation depends on the mass of the armature, on the field excitation, and upon those factors in the

design of the machine which affect the synchronizing power. It may probably be approximately represented by the following expression,

$$T \propto 2\pi\sqrt{\frac{M}{F}}, \text{ in which}$$

$M =$ moment of inertia of armature.

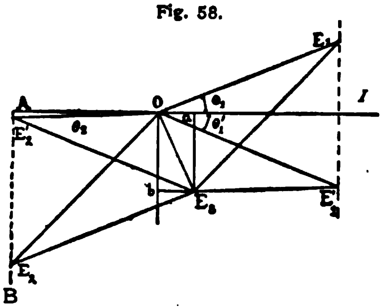
$F =$ moment of synchronizing force.

The machines are liable to get out of step when some periodic irregularity in the power of the driving motors accentuates the natural period or one of its harmonics.

This may occur either by resonance or interference. The latter is usually the case when the amplitude of the oscillations increases and decreases periodically.

The subject of the parallel running of alternators and the difficulties sometimes encountered is beyond the scope of this book and the reader is referred to the numerous papers on the subject which have appeared during the last few years. One of the controlling factors in the problem has been found to be the adjustment of the damping of the engine governors. When the machines begin to oscillate in speed with respect to each other it has been found that the governors, if they are too quick acting, hunt back and forth, so that the machines have to carry a heavy cross current and may even swing out of step. This difficulty has been frequently overcome by the use of dash pots to make the governors more sluggish in their action.

Fig. 58.



The parallel operation of synchronous machines is also greatly assisted by surrounding the poles with copper collars or by putting bridges of copper between them. The object of these devices is to prevent the periodic shifting of the field that accompanies the cross currents; any change in the lines of induction in the pole tips sets up eddy currents in the copper which tend to counteract the change in flux to which they are due.

In discussing the subject of alternators in parallel there are two distinct cases to be considered:

(*a*) Motor and generator.

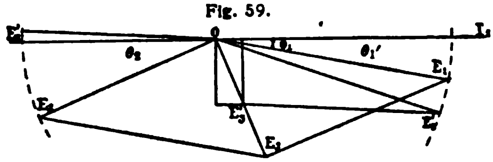
(*b*) Generators in multiple furnishing power to a distributing system.

These two cases had best be considered separately.

(*A*) Generator and Motor.

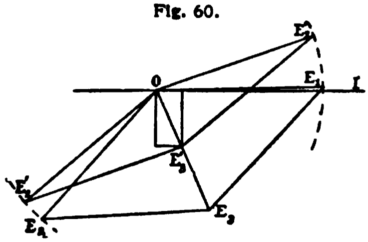
I. *Varying excitation, constant motor torque.* (Speed and impressed E.M.F. constant.)

Fig. 59.



In this combination of machines there are, for every value of the current, two distinct conditions. This is shown in Fig. 58. In one case the current leads the impressed voltage $\overline{OE_1}$ and in the other it lags behind it. The leading current corresponds to the larger value of $\overline{OE_2}$.

Fig. 60.



$\overline{OE_2}$ in this diagram must fall upon the line $\overline{AB}$ perpendicular to $\overline{OI}$, because the projection of $\overline{E_2}$ on OI, which represents the output of the motor, is a constant.

Increasing the motor excitation, therefore, evidently produces a leading current.

II. *Constant excitation, varying torque.* (Speed and impressed E.M.F. constant.)

Applying load to the motor will change not only all the phase relations, but also the amplitude of the current. Fig. 59 is designed to show the result of loading the motor when its excitation is such as to produce a lagging current at no load.

The energy transformed by the motor into mechanical work is:

$$P_2 = IE_2 \cos \theta_2.$$

As the load comes on the armature of the motor is held back so as to increase the lag of $\overline{OE_2}$, while $\overline{OE_3} = Z_m I$ increases until the above equation for P_2 is fulfilled.

It will be seen that increasing the load may bring the current into phase with the impressed E.M.F.

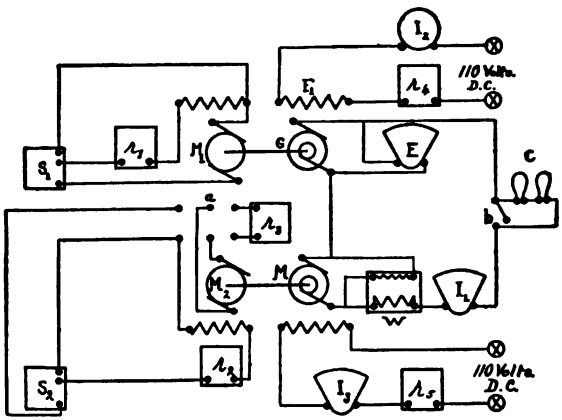
A similar action takes place if the motor excitation is such as to produce a leading current at no load. This is shown in Fig. 60.

Experiment 11. — External Characteristic of an Alternator at Constant Power Factor. (a) Leading Current. (b) Lagging Current.

In this experiment the object is to show the effect of the phase of the current upon the armature reaction. The leading and lagging currents are obtained by varying the excitation and the load of a synchronous motor.

In connecting machines in parallel, where a synchronizer is not available, lamps are ordinarily used. Fig. 61 shows the

Fig. 61.



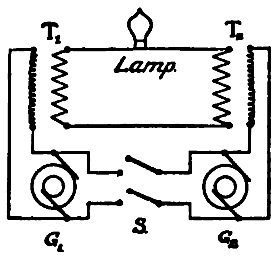
arrangement for a single-phase single-pole switch. A double-pole switch should have one of the lamps across each break, the rated voltage of each lamp being that of the alternator.

Polyphase connections are similar to single-phase, but it is necessary to make sure that the lamps in both phases go out at the same time. This indicates that the direction of electrical rotation is the same for both machines, which is obviously a necessary condition. It can always be brought about by interchanging the terminals of one phase. It is desirable but not absolutely necessary to close all the phases at once in polyphase work, as one phase will ordinarily be sufficient to hold the machines together until the others are closed.

In dealing with high potentials, transformers are used to step the voltage down to that of the synchronizing lamp. The connections can then be arranged if desired so that synchronism will be indicated when the lamps are bright; this, however, is not the general practice. The connections for single phase, using transformers, are shown in Fig. 62.

(*a*) *Method.* — Make the connections as shown in Fig. 61. Close switch *a* to the left, and start the machines, leaving switch *b* open. The synchronizing lamps will begin to flicker as the frequencies of the two alternators approach equality. When the voltages of *G* and *M* are equalized and so adjusted in phase that the lamp remains black for a number of seconds, the switch *b* may be closed, and the machines will run in synchronism. The switch *b* should be closed when the lamp is black, and as nearly as possible at the middle of the period of blackness; it is preferable, however, to close the switch when the machines are coming into phase rather than the reverse.

Fig. 62.



After the machines have been thrown together by closing switch *b*, the double throw switch *a* is to be thrown to the right.

G will now run *M* as a motor, and *M* will in turn drive M_2 as a generator furnishing current to r_3.

In order to determine the external characteristic of G with leading current, superexcite the field of M so as to produce a power factor of about 0.7. Apply load to M by drawing current from M_2 through r_3. As the load increases it will be necessary to increase the excitation of M in order to keep the power factor constant.

(*b*) *Method.* — Proceed throughout in the same manner as in (*a*) except that the current must be lagging and not leading.

It is possible to distinguish a leading from a lagging current in the following way. Vary the field of M slightly, and observe the effect on the reading of the ammeter I. If the current is leading, increasing the field strength of M will increase the current I, but if the current is lagging it will decrease it. In this connection see Fig. 58.

Field Amps of Motor.	Field Amps of Generator.	Arm. Amps.	Arm. Volts.	K.W.	Power Factor.	Speed.	Remarks.

N. B. — Keep the frequency, the A. C. generator field current, and the power factor constant. Take five readings.

Report. — Plot two characteristic curves, (*a*) with leading current, (*b*) with lagging current, taking terminal volts of G as ordinates, and the current values, I, as abscissæ.

Plot these curves on the same sheet, and to the same scale as the curve of Experiment 10. All three curves should start from the same no-load voltage.

THE SYNCHRONOUS MOTOR.

Characteristic Curves.

Experiment 12. — With Normal Field Current Determine the Curve of Commercial Efficiency.

The best way to determine the efficiency of any motor is by a brake test, which, if properly performed, gives reliable results. In the case of motors above 100 H. P. it becomes troublesome and expensive to make the test in this way, and the efficiency is usually calculated from the equation,

$$\text{Eff.} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

The value of the losses for any desired output is the sum of the ohmic and load losses as obtained in Experiment 8*a*, friction and windage including brush friction, the watts lost in the field winding and rheostat and the core loss, the latter being obtained as described under Experiment 8*b* at the rated voltage and unity power factor. It will be seen that in order to calculate the current losses some number of amperes must be assumed. This may be done by calculating the current which at the rated voltage corresponds to the output and dividing the resulting value by the probable per cent. efficiency of the motor.

Where the machine under test has been put through a heat run it is usual to employ the observed temperature rise of the armature and field conductors in order to calculate the resistances at an assumed room temperature of 25° C. The final temperature then becomes equal to 25 + temperature rise in degrees C. Knowing the cold resistances, the values for this temperature may be calculated by assuming an increase in resistance of .4 per cent. per degree C. In the absence of a heat run the final temperatures may be estimated by means of data obtained from other machines of similar type previously constructed, or the cold resistances may be merely increased by 10 per cent.

The friction and windage losses can be obtained by noting the

power required to run the motor free at the proper frequency with minimum armature current, and subtracting from it the ohmic loss plus the core losses corresponding to the field current. The value thus obtained should correspond with the value of friction plus belt loss found in Experiment 8.

Report. — Plot the values of efficiency in per cent. as ordinates, with horse-power output as abscissa.

Experiment 13. — At no load and full load, determine the curves of current, power factor and watts input in relation to the motor field current.

The relation between the armature and field currents of a synchronous motor at any fixed torque is commonly called its *phase characteristic.* In commercial work this test is usually carried on at no load, but it will sometimes be found desirable to make it at various outputs in order to find the effect of the load current upon the value of the field excitation necessary to produce any particular power factor which may be required.

The dependence of the power factor upon the field excitation has been explained on page 134 in connection with Fig. 58. Since the energy transformed into work by the motor is constant at any definite output except for core loss variation, the armature current must, therefore, vary with the field excitation on account of the variation in power factor which accompanies any change in the field.

The torque developed by the motor can never be greater than that required to drive the machine at synchronous speed, consequently, if the field current is weakened the armature becomes slightly displaced in phase, so that even with the increased armature current the torque remains the same as before except for changes in the losses of the machine. Weakening the field, therefore, tends to displace the motor armature ahead, in the direction of rotation, while strengthening the field tends to produce a mechanical lag. Fig. 58 shows, however, that in the electrical circuit the conditions are reversed, thus under-excitation produces an electrical lag, making the current lag behind the ter-

Field Watts = Impressed Volts = Frequency =

Short Circuit Core Loss	Open Circuit Core Loss	No Load Input	I^2R Loss	Friction Loss	Load Loss	Arm. Amperes	K.W. Output	Brake H.P.	K.W. Input	Efficiency

minal volts while superexcitation on the contrary causes it to lead.

Method. — Bring the motor up to speed, and synchronize by the method of Experiment 11. Operating the machine at no load, keep the impressed E.M.F. constant, and note the ammeter and wattmeter readings at successive values of the field current. Vary the field through as wide a range as possible without throwing the motor out of step. Repeat the series of readings at full load.

The tabulation of readings should be the same as in Experiment 11.

N. B. — Keep the impressed volts and the frequency constant. Take ten readings in each case.

Report. — Calculate the values of power factor from the instrument readings. Plot the results in the form of a curve with field amperes as abscissæ. On the same sheet, with the same abscissæ, plot the curves of current and watts.

The no load and full load curves are to be plotted on two separate curve sheets.

Experiment 14. — With Constant Motor Excitation and Variable Torque, Determine the Curves of Current and Power Factor.

On page 134 it has been shown that with both impressed and counter E.M.F.'s constant, the phase relations vary with the load. The object of this experiment is to show the nature of this variation.

D.C. Generator.		A.C. Motor.				Speed.	Torque.	Remarks.
Amperes (Line).	Volts.	Field Amps.	Arm Volts.	K.W.	Power Factor.			

Method. — Use the same connections and method of synchronizing as described in connection with Experiment 11. Note the

current and watts taken by the motor *M* at various loads, keeping the motor excitation constant.

Take two series of readings:

(*a*) With under-excited motor field. The conditions will here correspond to Fig. 59.

(*b*) With super-excited motor field. The conditions will be those shown in Fig. 60.

In both (*a*) and (*b*), vary the load as far as possible without throwing the motor out of step.

N. B.—Keep the impressed E.M.F.'s, the motor field and the frequency constant. Take eight readings.

Report. — Plot the two sets of curves of (*a*) and (*b*) on thc same sheet, using values of current and power factor as ordinates, and torque in foot lbs. as abscissæ.

(*B*) Two Alternators in Parallel Supplying a Constant Potential Distributing Circuit.

A. C. generators in multiple act much in the same way as will any plurality of machines linked together by an elastic coupling. Each element driven by its own prime mover operates in strict synchronism with all the others; its exact phase relation or angular position relative to the others is, however, dependent on the torque developed by its prime mover and by the tension exerted by the elastic link which holds it in step. Each alternator may, in fact, be shifted angularly by any change in its field excitation, an increase producing a mechanical lag, and a cross current is simultaneously produced which by its torque acts like an elastic force tending to hold the machines together. Too great a modification in the excitation of a machine may indeed overstrain this synchronizing force to the breaking point and the machine will fall out of step. Oscillation of the moving members of the alternators with respect to each other may also produce this result.

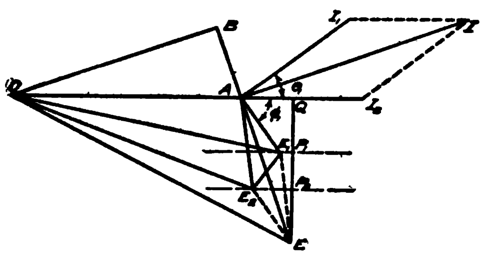
If the armature circuits had no impedance it is obvious that

all the machines would develop the same voltage. In practice, the cross armature currents due to unequal field currents, flow so as to strengthen the weaker and weaken the stronger fields by armature reaction; they are really magnetizing currents transferring field excitation from one machine to the other, and tending to equalize the induced E.M.F.'s.

The division of the load between synchronous engine-driven alternators is practically unaffected by changes in field excitations, and the only way to alter it is to change the relative torque exerted by the engines. This is done by controlling the throttle valves or governors.

The general principles involved are brought out by the vector diagram, Fig. 63, which relates to two alternators in multiple

Fig. 63.



operated at constant speed and sharing the load unequally, with unequal field excitations. $\overline{OA}$ represents the line voltage supplied at the bus bars, while $\overline{OB}$ and $\overline{AB}$ represent respectively the energy and wattless components of the line voltage, which is displaced from the load current by the angle AOB.

If the load were all supplied by a single alternator of negligible ohmic resistance, the induced E.M.F. of this machine would be given by the line $\overline{OE}$, and the internal inductive drop due to armature reactance, by the line $\overline{AE}$ which, being at right angles to the direction of the current, will be in the prolongation of $\overline{AB}$.

If the load is taken by two machines instead of one, their E.M.F.'s will be represented by lengths $\overline{OE_1}$ and $\overline{OE_2}$ which are not shown by lines to avoid confusing the diagram. Since the two machines together are to be equivalent to the single machine of internal drop $\overline{AE}$, it is plain that the unequal reactance drops $\overline{AE_1}$ and $\overline{AE_2}$ must complete the parallelogram of which $\overline{AE}$ is the diagonal. Their lengths will also be directly proportional to the corresponding armature currents.

It can readily be shown that the power developed in the distributing circuit by each of the two alternators is proportional to the projections of $\overline{AE_1}$ and $\overline{AE_2}$ upon a perpendicular to the line $\overline{OA}$ drawn from the point E. To prove this, let us write the equation

$$\overline{P_1Q} = \overline{AE_1} \sin \phi_1.$$

We have seen that $\overline{AE_1}$ is proportional to the current developed in the distributing circuit by the alternator whose E.M.F. is E_1. The direction of this current is along the line $\overline{OI_1}$ at right angles to $\overline{AE_1}$. The power developed in the distributing circuit by the current $\overline{OI_1}$ is

$$W_1 \propto \overline{AE_1} . \overline{OA} \cos \theta_1.$$

Since $\overline{OA}$ is a constant,

$$\overline{AE_1} . \overline{OA} \cos \theta_1 \propto \overline{AE_1} \sin \phi_1.$$

Hence, $$W_1 \propto \overline{P_1Q}.$$

As explained above, the power developed by each machine in the distributing circuit is a constant depending on the torque of the driving motor. If therefore, the excitations of the alternators are varied, the points E_1 and E_2 will move along lines parallel to $\overline{OA}$ through the points P_1 and P_2.

The I^2R losses of the two machines will be a minimum when the sum of $\overline{AE_1}$ and $\overline{AE_2}$ is a minimum. This is the case when E_1 and E_2 both lie on the line $\overline{AE}$.

The machine whose E.M.F. is given by the line $\overline{OE_2}$ has the greatest lead, furnishes the most current, and is doing the most work. Its driving motor is the one exerting the greater torque.

If the length $\overline{OE_2}$ is increased by raising the excitation of the machine in question, this E.M.F. will come more into phase with that of the line, and cause the point E_2 to approach the line $\overline{AE}$ which is the position of maximum economy. A similar result is obtained by diminishing $\overline{OE_1}$.

Experiment 15.—Adjustment of the Alternator Excitations for Maximum Economy, each Machine Taking the Same Share of the Load.

The conclusions that follow from the preceding discussion are that although each alternator must always bear a share of the load, depending on the torque of its driving motor, its phase relation to the other alternators running in parallel with it can be changed by varying the field current.

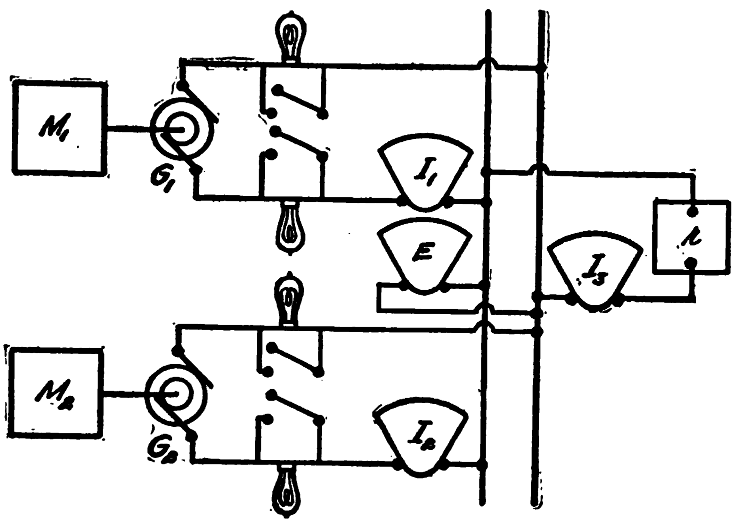
Two alternators in parallel are therefore quite different in their operation from direct-current generators. If one of the engines tends to govern for a higher speed, its alternator will take the load off the other machine, and although both continue to revolve in synchronism their E.M.F.'s will be displaced in phase with respect to each other, and a local current will flow in the circuit formed by the two armatures. This local current is proportional to the lines $\overline{a_1E_1}$ and $\overline{a_2E_2}$ which represent the reactance drops due to it. These are equal to each other, for if there are only two machines, the cross current must be the same in both armatures. The actual vector representing the cross current would be a line displaced by 90° from the line $\overline{a_1E_1}$ and therefore at right angles to the line voltage $\overline{OA}$, and consequently wattless as regards the external circuit.

With two equal machines it is evident that both should develop the same output, and that their excitations should be such as to give zero cross current. These are then the conditions under which the machines are operated most economically.

If the turning moments of the prime movers remain equal, and the excitations of the machines are out of adjustment, so that the E.M.F.'s, $\overline{OE_1}$ and $\overline{OE_2}$ are unequal, it is evident that the cross current at right angles to $\overline{E_1E_2}$ will be practically wattless. The effect of this wattless cross current due to unequal excitations is to magnetize the field of the underexcited machine and demagnetize that of the superexcited machine, thus tending to equalize the excitations.

Method. — Make the connections as shown in Fig. 64. Bring one of the alternators G_1 up to its rated speed and voltage, connect it to the distributing circuit and cause it to supply current to

Fig. 64.



the distributing circuit. Next synchronize G_2 and throw it in parallel with the bus bars; if this operation is accurately carried out no current will be supplied by G_2 to the line. In order to divide the load equally between the machines, it is necessary to adjust the governor of the engine connected to G_2 so as to increase its torque; this will automatically diminish the torque of M_1, and when both prime movers exert the same driving power, it will be found that both machine ammeters show the same read-

ing, and any cross current can then be practically reduced to zero by adjusting the field excitations, care being taken not to alter the bus bar voltage by so doing. If the alternators are driven by direct current motors, G_2 must be made to take its share of the load by weakening the field, and thus increasing the torque of the motor driving it. At the same time the field of the motor driving G_1 must be correspondingly strengthened.

In regulating the voltage of the bus bars, the excitation of each machine may have to be altered, so as to keep the sum of the machine ammeter readings a minimum. In practice where power factor meters are used, each field may be adjusted so as to make the power factor of the corresponding machine a maximum.

Take readings of all the instruments under the following conditions.

(*a*) G_1 operated alone, and supplying its full load current to the distributing circuit at its rated voltage.

(*b*) G_1, as before, and G_2 in parallel with the line but taking no load.

(*c*) G_1 and G_2 supplying equal power to the distributing circuit and the sum of the machine ammeter readings equal to the load current, or nearly so.

(*d*) G_1 and G_2 sharing the load unequally. Adjust the excitations so that the sum of the machine ammeter readings is a minimum.

(*e*) G_1 and G_2 sharing the load equally but with unequal excitations and consequently unequal induced E.M.F.'s.

During all the above operations the voltage of the bus bars must be kept constant as well as the load current.

Report. — Tabulate the readings obtained, giving a full discussion of the significance of each portion of the experiment and of the observations corresponding to it.

Tests on Transformers.

Experiment 16. — Determination of the Core Losses.

These losses are due to hysteresis and eddy currents consequent upon the oscillations of the magnetic flux. In a well-designed constant potential transformer they are practically independent of the load.

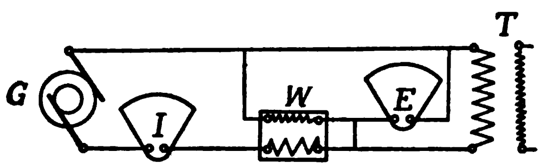
Method. — To determine the core losses of a transformer, connect the low voltage side to an alternator, as shown in Fig. 65. Adjust the voltage and frequency to the rated values. The magnetization will then be that for which the transformer was designed and the corresponding core losses will be present.

Note the instrument readings.

In order to study the effect of varying the frequency and impressed voltage take readings with normal voltage at frequencies 25 per cent. and 50 per cent. above and below normal frequency. Then at normal frequency take four sets of readings at the same fractions of normal voltage.

In all cases the copper losses will be negligible. This is because the current flowing is only a small fraction of the full load current, while the copper losses are proportional to its square. Should not this be really the case, the small I^2R loss may be readily calculated and subtracted from the wattmeter reading, thus obtaining the true core losses. The ammeter reading will give the exciting current.

Fig. 65.



The energy used in the pressure coil of the wattmeter should, however, be subtracted from this reading.

It will be found that a slight alteration of the frequency will produce no appreciable change in the core losses if the voltage is

kept constant. This is because

$$W = K_1 B^{1.6} f + K_2 B^2 f^2;$$

and at constant voltage, the induction is inversely proportional to the frequency.

If there were heavy magnetic leakage in the transformer, the core losses might be different depending on which coil was connected to the alternator. This, however, will not occur in any modern constant potential transformer.

Report. — Calculate the values of power factor. With impressed voltage as abscissa plot on the same sheet the curves of watts, amperes and power factor. On a second curve sheet plot the corresponding curves with respect to frequency as abscissa.

Experiment 17. — Determination of Copper Losses, Impedance and Regulation.

In order to find the copper losses it would be sufficient to determine the resistances of the transformer windings, and the current in each of them. There are, however, additional losses due to local hysteresis and eddy currents, caused by the currents in the windings. These are known as "load losses," and they are measured together with the copper losses by the method of this experiment. It is probable that these load losses are greater at short circuit than under normal conditions. This method of measurement will therefore make the losses appear a trifle greater than they are under working conditions.

The impedance of the transformer is obtained by dividing any voltmeter reading by the current corresponding to it. It will be found that the resulting value does not change materially for a wide range of current.

The alternator or other source of current used in this test must be capable of furnishing the full-load impedance voltage of the transformer which will probably not be more than 10 per cent. of the rated voltage of the transformer. It is usual to connect the high voltage winding to the source of power, as shown in Fig. 66, the low voltage secondary being short circuited on

itself; practically the whole of the impressed voltage is then consumed over the impedance of the two transformer windings, since the secondary is short circuited, and the wattmeter reading represents the copper and load losses. The value of the impedance is

$$Z = \frac{E}{I} = \sqrt{(R_1 + a^2R_2)^2 + (X_1 + a^2X_2)^2},$$

R_1, X_1 and R_2, X_2 being the primary and secondary resistances and reactances, and a, the ratio of turns. It will be seen that this determination does not separate X_1 and X_2, but merely gives their sum. As a matter of fact the equation

$$X_1 = a^2X_2,$$

is approximately true unless a is very great. It is evident that in what precedes a is greater than unity. The resistance R_1 and R_2 at the low frequencies now employed are substantially equal to the ohms of the primary and secondary windings; theoretically, however, the effective resistance due to the load losses are also included in R_1 and R_2.

The two preceding equations show that the calculated value of Z when the high tension side of the transformer is connected to the alternator, is theoretically independent of the number of secondary turns, provided the dimensions and relative positions of the primary and secondary coils remain practically unchanged for different values of a. Z is therefore the ohms impedance of the transformer, assuming the secondary to have the same number of turns as the primary. If the windings are interchanged so as to connect the secondary to the source of power, with the high voltage side short circuited, the impedance is then similarly obtained in terms of the number of secondary turns.

The regulation of a transformer is equal to the secondary no-load voltage minus the full-load voltage divided by the full-load voltage. The latter quantity is obtained by subtracting vectorially the impedance drop in both windings from the no-load voltage.

The relations between the no-load, full-load and impedance E.M.F.'s are shown by the corresponding lines $\overline{OE_0}$, $\overline{OE}$ and $\overline{oe}$ in Figs. 53 and 54, from which it will be seen that the regulation of a transformer depends on the power factor of the load. The same thing is true of a generator and of a transmission line, the same diagram being applicable to all. It is for this reason that unless otherwise stated the regulation of a transformer is always calculated for non-inductive load, or θ equal to zero.

In Fig. 53 let the angles between $\overline{OE_0}$ and I and between $\overline{Oe}$ and I, be denoted respectively by γ and ϕ. Using the method of complex quantities we have

$$\overline{O\dot{E}} = \overline{O\dot{E}_0} - \overline{O\dot{e}}$$

$$\overline{O\dot{E}_0} = \overline{OE_0} \cos \gamma - j\overline{OE_0} \sin \gamma, \text{ and}$$

$$\overline{O\dot{e}} = \overline{Oe} \cos \phi - j\overline{Oe} \sin \phi$$

Hence,

$$\text{Regulation} = \frac{\overline{OE_0} - \overline{OE}}{\overline{OE}}$$

$$\text{"} \quad = \frac{\overline{OE_0} - \sqrt{(\overline{OE_0} \cos \gamma - \overline{Oe} \cos \phi)^2 + (\overline{OE} \sin \phi - \overline{OE_0} \sin \gamma)^2}}{\sqrt{(\overline{OE_0} \cos \gamma - \overline{Oe} \cos \phi)^2 + (\overline{Oe} \sin \phi - \overline{OE_0} \sin \gamma)^2}}$$

$$\text{where } \gamma = \theta + \sin^{-1} \frac{Oe}{OE_0} \sin \left[180° - \phi + \theta\right]$$

$$\overline{Oe} = IZ, \quad \cos \theta = \text{load power factor,}$$

and,

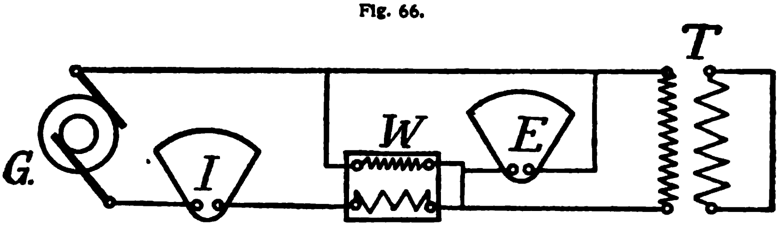
$$\phi = \cos^{-1} \frac{(R_1 + a^2 R_2)}{Z}$$

In these equations $\overline{OE_0}$ is the no load E.M.F. of the low voltage winding, and Z is the impedance determined with the high potential winding connected to the source of power as shown in Fig. 66. The preceding calculation neglects the small drop due to the magnetizing current.

Method. — Connect the apparatus as in Fig. 66 and adjust the speed of the generator to give the rated frequency of the transformer under test. Beginning with a small value of the impressed voltage take a series of ten readings of ammeter voltmeter and wattmeter, carrying the test up to full load current.

Report. — Plot a curve with the wattmeter readings as ordinates, and amperes as abscissæ. Calculate the I^2R losses of both windings and plot a second curve on the same sheet as the previous one with these I^2R watts as ordinates. The difference between these two curves approximately represents the load loss of the transformer for any value of the current.

Fig. 66.



Calculate the average value of Z and determine the regulation at full load for $\cos\theta = 1$ and $\cos\theta = 0.7$.

Experiment 18.—Operation of a Transformer and Determination of the Efficiency Curve.

Method.— Make the connections as shown in Fig. 67. Keeping the frequency and impressed voltage constant at their rated values take readings of the instruments at 0, ¼, ½, ¾, and full load.

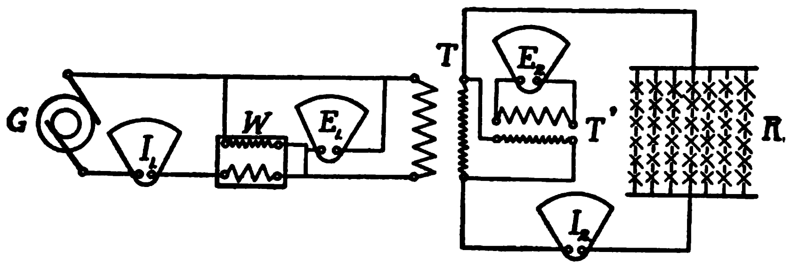
Frequency - *Impressed Volts* - *Exciting Current* -

Output			Input						
Amperes	Volts	K.W.	Amperes	Iron Losses	Copper Loss + Load Loss	K.W.	Power Factor	Efficiency

In this diagram the transformer T' represents a potential transformer. If both windings of the transformer under test, T, are low voltage, T' may be omitted, and a water rheostat may be used in place of the series lamp load R.

Report. — Calculate the regulation of the transformer from the voltmeter readings at full load, and compare the corresponding value determined in Experiment 17.

Fig. 67.



Using the values of the losses determined by means of the wattmeter in Experiments 16 and 17 calculate the efficiency curve of the transformer at ten successive values of the load up to full load with K. W. output as abscissæ. From the same data calculate the curve of power factor for the various values of current output, and plot the results on the same sheet and to the same scale as the efficiency curve.

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}},$$

$$\text{Power factor} = \frac{\text{watts input}}{\text{volt-amperes input}}.$$

In calculating the current corresponding to a given output the regulation should be taken into account, thus at 100 K. W. output the current will be 3 per cent. greater if there is a 3 per cent. drop in voltage than if there is no drop. The impedance of a transformer being very nearly constant below full load, the internal impedance drop, may be assumed to be proportional to the current.

Experiment 19. — Heat Test by the Motor Dynamo Method.

The advantage of this method lies in the fact that the conditions of full load are practically reproduced as far as heating is concerned, without any considerable waste of energy. It requires a constant potential source of alternating currents G_2, Fig. 68, which furnishes power for the core losses, and a second low voltage source, G_1 which supplies the current losses. G_1 is frequently the secondary of an auxiliary transformer instead of a generator as shown in the diagram. This method derives its name from its general similarity to "feeding back" methods where generators are tested in pairs, one machine acting as a motor and the other as a generator. It is evident of course that a single transformer may be subjected to a heat run by operating under load under normal conditions.

The measurement of the temperature of the coils of the two transformers is made by noting the rise in resistance, either with a wheatstone bridge or by the fall of potential method, depending on whether the coils are of high or low resistance. The connections for the latter method are shown in the diagram.

Method. — Make the connections as shown in Fig. 68. The room temperature must be read from one or more thermometers suspended in the immediate neighborhood.

Additional thermometers should be fastened inside the transformer cases so as to determine the temperature of the coils, the oil or air, the laminations and the iron of the case.

Before beginning the test, the transformer being as nearly as possible at room temperature, note all thermometer readings and measure the resistance of all coils. In the method of Fig. 68 this is done by opening m'' and closing the switches m and m' upwards. By adjusting the resistances r_1 and r_2, small currents, insufficient to produce appreciable heating, are sent through the primary and secondary windings of the two transformers. With an observed current, the drop in voltage across each coil of both transformers is then read by means of a millivoltmeter. Care must be taken to remove this instrument before varying or

interrupting the current, as it may otherwise be injured by the induced voltage developed by the accompanying change in the magnetic flux.

In order to begin the heat run, switch *m* is closed downwards and *m''* is also closed. Adjust the frequency and voltage of G_2 to the rated values for the transformers under test. Since the two low voltage coils are in multiple, full magnetization and the corresponding core losses will be present.

The connections of the high voltage coils must be arranged so that the E.M.F's induced in them shall be in opposition, and when this is the case the difference of potential between. the two outside terminals of the pair will be zero. It is well to make sure of this by means of a suitable A.C. voltmeter before bringing the voltage up as described.

With the voltage of G_1 at zero, close the switch *m'* downwards and build up the voltage of G_1 by small increments until the A. C. ammeter indicates full load current. The frequency of this current and E.M.F. need not be exactly the same as that of the E.M.F. supplying the core losses.

It will be evident that in the circuit of the current produced by G_1 the algebraic sum of the induced E.M.F.'s is zero since they are equal and opposite to each other. This current will, therefore, only be opposed by the internal impedance of the two transformers.

Since the ratio of transformation holds under the conditions described, the current I produced by G_1 in any one of the windings of a transformer will be accompanied by a current in its other winding corresponding to the ratio of transformation. It is plain, that the source G_1 will supply full copper losses to both transformers, together with the accompanying load losses.

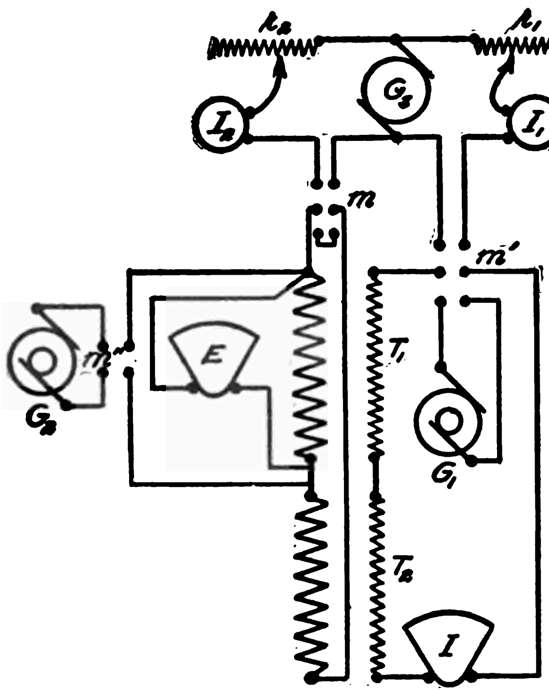
With the arrangement described, the heating of the transformers will be practically the same as in normal operation since all of the energy losses are present.

In testing large transformers of very high voltage it is customary to insert the A.C. source G_1 in the wire connecting the

ends of the two low voltage windings together, leaving the high voltage circuit closed upon itself and insulated, during operation, from all auxiliary apparatus.

A single three-phase transformer may be tested by connecting the coils in delta. The generator G_2 is then three phase, and is connected to the points of the delta in the ordinary manner so as

Fig. 68.



to bring the transformer up to normal voltage and frequency. G_1, however, remains single phase, and is inserted into any leg of the primary or secondary delta as desired.

The load conditions are to be maintained in this test until the transformers have reached constant temperature. During this interval of time take six sets of readings of all thermometers and of coil resistances. This is done by opening switch m'' and

closing switches m and m' upwards; the D.C. drop across all coils should then be quickly taken, noting the readings of I_1 and I_2. Having removed the millivoltmeter close switches m and m' downwards, close switch m'' and allow the heat test to proceed.

N. B. — Keep E, I and the frequency constant. The relation between temperature and resistance is expressed in the following equation:

$$t = t_1 + \frac{R - R_1}{.004 R_1}.$$

In this expression

R_1 = res. at beginning of test.

t_1 = temp. of coil at beginning of test, in degrees Centigrade.

R = res. at any subsequent temp. t.

In order to express the result in degrees Fahrenheit,

Degrees Fahrenheit = Degrees Centigrade $\times \frac{9}{5} + 32$.

In order that the initial temperature may be known, the transformer should be left over night in the testing room which should be kept at constant temperature. The temperature of all parts of the transformer will then be the same as that of the air.

Report. — For each transformer plot three curves on the same sheet:

1. Temperature of primary winding by resistance.
2. " of secondary winding by resistance.
3. " of interior.
4. " of laminations.
5. " of case.

State whether or not oil is used in the transformer.

In plotting the curves, make temperature the ordinate and time the abscissa.

Curve Tracing.

Determination of the Voltage and Current Curves of a Transformer under Various Conditions.

Experiment 20. — With the Secondary Circuit Open, Determine the Following Curves:

(*a*) Primary E.M.F.

(*b*) Primary current.

(*c*) Secondary E.M.F.

In a transformer, the phase relations and wave shape of the exciting current are of considerable interest, as they present peculiarities which are not yet thoroughly understood. The angle of lag is practically independent of the frequency, and varies with the induction and the nature of the iron. If the E.M.F. is a sine wave, the current will be distorted showing the presence of upper harmonics, but considerable changes in the frequency will make no very marked changes in its shape.

The form of the primary current wave depends, in general, upon the nature of the secondary current. The primary current is the result of the complex harmonic exciting current and of a component which depends on the secondary current output. With a heavy lamp load, the primary current will be almost in phase with the E.M.F. and similar in form. This is because the exciting current is then so small compared with the total current that its effect is negligible.

The shape of the E.M.F. wave depends on the design of the armature of the alternator and on the field distribution. A smooth core armature will, in general, give a near approach to a sine wave. It is desirable in these experiments that the E.M.F. curve should be sinusoidal, as that is the standard form of wave.

The primary and secondary terminal volts will always be found to differ in phase by exactly 180°, except for a small displacement due to the drop in the windings.

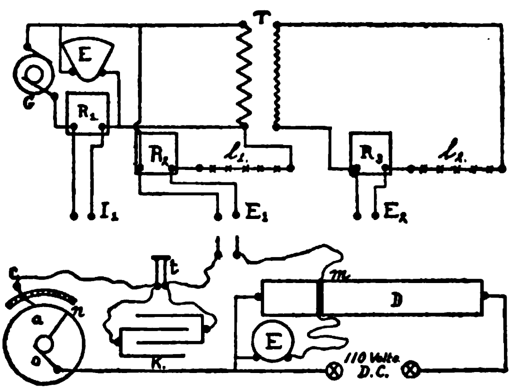
Very many systems of curve tracing have been proposed. That which is described in this experiment is the well known

method of instantaneous contact. While not a rapid method, it is accurate and easy to construct. The principle involved is that the required curve may be obtained by balancing the instantaneous value of the alternating E.M.F. against a known direct E.M.F.

Method. — In Fig. 69 the connections are shown for determining the curves of this experiment. R_1 is a non-inductive resistance sufficiently large to give a small voltage drop when traversed by the exciting current of the transformer T. The drop across R_1 will be proportional to the current at any instant, and the curve of this drop will be the same in form as the curve of the current.

R_2 and R_3 are adjustable non-inductive resistances placed in series with the lamp boards l_1 and l_2. By taking the drop across

Fig. 69.



R_2 and R_3 it is possible to obtain a fraction of the primary and secondary voltages, respectively.

D is a rheostat fitted with a sliding contact m. By moving m along the drum it is possible to obtain a gradually varying D. C. voltage, which may be read on the voltmeter E. This voltage is used to balance against the drops at I_1, E_1 and E_2 in determining the curves.

When the voltages are high it is best to substitute potential transformers to step down from the main transformer voltage to suitable values for E_1 and E_2; l_1, l_2, R_2 and R_3 are then omitted.

I_1, E_1 and E_2 are receptacles into which the spring jack in circuit with the telephone receiver t may be inserted.

a represents a disc mounted on the shaft of the alternator. The brush c is mounted so that its angular position may be varied. Its use is to pick out instantaneous values of the E.M.F.'s I_1, E_1 and E_2. Contact will be made at n at the same point in each successive period, thus giving the corresponding instantaneous value of the E.M.F. Successive instantaneous values may be obtained by shifting the angular position of the brush c.

Insert the spring jack in any one of the receptacles as I_1. A note will be heard in the telephone receiver unless the voltage E exactly balances the drop across R_1 at the instant when the brush c makes contact at n.

Move the point m along the drum until silence is obtained in the receiver. The reading of the voltmeter E will then be equal to the instantaneous values of the drop R_1I_1 corresponding to the angular position of the brush c.

By taking a series of readings in this way at successive positions of c, the desired curve may be obtained.

Proceed in this manner in determining all the required curves. In order to work more quickly, take a reading of I_1, E_1 and E_2 for each setting of the brush c.

Since only the form of the curves, and not their magnitude is required, it will not be necessary to know the value of R_1, R_2 and R_3. It is evident that potential transformers may be substituted for the resistances l_1, l_2, R_2 and R_3, and a current transformer may be made to take the place of R_1.

N. B. — Keep the impressed voltage of the transformer, and the frequency constant. Take readings every ten electrical degrees for one half of a period.

Report. — Plot all the curves on the same sheet.

The curves must be plotted so that time is counted from left to right. Whether the readings run in this way or not will depend on the direction of rotation of the contact disc relatively to the rotation of the machine. This is an important point, as it involves

the phase relations of the curves. Care must also be taken not to plot the curves so that some appear upside down, or displaced 180° in phase, which will be the case if negative values are mistaken for positive.

At twenty equidistant points on the time abscissa within the range of a half period note the ordinates of the primary voltage and current curves. In the case of each of the two curves calculate the square root of the mean square of these ordinates. This will give the effective values. On the same curve sheet construct the watt curve by multiplying corresponding ordinates of primary volts and amperes together. Integrate the watt curve through a half period. The resulting area when expressed in terms of the coördinates will give the joules per half cycle. Knowing the frequency, calculate the joules per second, or average watts. The same result may obviously be arrived at by taking an average value of twenty equidistant ordinates of the watt curve in a half period.

Obtain the power factor by dividing the watts by the product effective volts and amperes. Find the angle whose cosine corresponds to the value of the power factor, and compare it with the angular distance between the zero points of the curves of primary volts and amperes.

Experiment 21. — With Full Load on the Secondary Determine the Following Curves.

(*a*) *Primary E.M.F.*
(*b*) " *Current.*
(*e*) *Secondary E.M.F.*
(*d*) " *Current.*

It will be found that by loading the transformer with an inductive load in which there is no iron, the primary current is correspondingly increased, and becomes practically of the same form as the E.M.F. The phase of the secondary E.M.F. will lag a little more than 180° behind the primary E.M.F. owing to the impedance drop in the coil. It must be remembered that the terminal volts are measured, and not the induced volts.

The shape of the E.M.F. wave will probably be altered owing to armature reaction.

It should be borne in mind that primarily the shape of the E.M.F. depends wholly on the design of the machine.

Load the secondary with an inductive load.

Method. — Determine these curves as well as those of Experiments 22 and 23 by the method of Experiment 20.

Report. — Plot all four curves on the same sheet, being careful to plot the results correctly, both with regard to their sign and to the direction in which the time as abscissa is counted, as explained in the last experiment.

Experiment 22. — Determination of the Curves of Experiment 21, the Secondary Circuit being Connected to the Primary of a Second Transformer.

Since the secondary of the second transformer is on open circuit, the secondary current curve of the transformer under test will be a complex harmonic, because it is an exciting current. The primary current curve will be practically the resultant of the exciting currents of the two transformers, and all the complexities of the secondary current will appear in the primary.

The connections in this experiment are the same as those of Fig. 69 except that the primary of the second transformer takes the place of the inductive load of the last experiment.

Experiment 23.—Determination of the Curves of Experiment 22, the Secondary Winding of the Second Transformer Carrying Full Load Current.

The load should be similar to that of Experiment 21.

Both the primary and secondary currents of the transformer under test will be increased, and will approach the form of the E.M.F. curve.

Each of them is the resultant of its value as in Experiment 22, and of a component corresponding to the current drawn from the secondary of the step-down transformer.

The connections in this experiment are the same as in Experi-

ment 22, except that the secondary of the step-down transformer is fully loaded.

Resonant Rise of Potential.

Experiment 24. — Connect a Condenser in Series with an Inductance to an Alternator. Determine a Curve with Condenser Voltage as Ordinate and Frequency as Abscissa.

The current in the circuit is

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}},$$

where E is the impressed E.M.F. It is plain that for any values of L and C there is a certain value of the frequency which will make the impedance a minimum, and

$$\omega L = \frac{1}{\omega C}.$$

The period of the impressed E.M.F. will then be equal to the natural period of the circuit, and the so-called condition of resonance prevails. When the resistance of the circuit is very small, this period becomes

$$T = 2\pi\sqrt{LC}.$$

Under these circumstances, therefore, the inductance and capacity reactions balance each other, and the only thing which opposes the impressed E.M.F. is the ohmic resistance which we have assumed to be small compared to the reactance; consequently, even if the E.M.F. impressed on the circuit is small, the current may become very great. As the current I increases so also do the E.M.F.'s, ωLI and $I/\omega C$, across the inductance and condensance respectively. These E.M.F.'s are equal to each other in amplitude at the frequency of resonance, the former being 90 degrees ahead of the current, and the latter lagging behind it by the same amount. At any instant, therefore, the algebraic sum of these E.M.F.'s is zero, although each of them may be very great compared with that impressed on the entire circuit.

The simple example of resonance described here is only one of many combinations by which resonant effects may be obtained; in every case, however, the same principles are involved.

Method. — Connect an electrostatic voltmeter across the condenser. Run the alternator at three quarters speed and low voltage. Keeping the speed constant, adjust the inductance and capacity until resonance is reached. Raise the voltage of the alternator by varying its excitation so that the point of maximum resonant voltage gives a reading well up on the scale of the electrostatic voltmeter. The required curve may then be determined by reading the condenser voltage at various frequencies. The voltage of the alternator must be kept constant by regulating the field current. Take ten readings. Vary the speed throughout a sufficiently wide range to include the entire rise and fall of the voltage.

N. B. — Keep the inductance, condensance and generator volts constant.

Report. — Plot a curve with condenser voltage as ordinate and frequency as abscissa.

Experiment 25. — Resonant Rise of Potential Obtained by Means of a Superexcited Synchronous Motor.

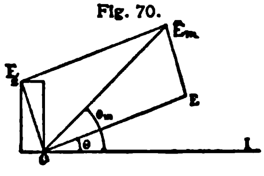
The curves to be determined are:

(*a*) Voltage at motor terminals as ordinates and frequency as abscissa, with constant motor excitation.

(*b*) Voltage at motor terminals as ordinates and field currents as abscissæ, with constant frequency.

In an alternating current transmission system it is possible to correct for the drop on the line by connecting a synchronous motor with superexcited field in parallel with the load. This effect is due to the fact that the leading current taken by the motor neutralizes the lagging current on the transmission line.

Fig. 70.



If the distributing circuit is open, and the generator is feeding the motor alone, the effect is much more marked.

The conditions may be understood by a consideration of Figure 70.

$\overline{OE_m}$ = Voltage at motor terminals.

$\overline{OE}$ = Voltage at generator terminals.

$\overline{OE_s}$ = Voltage due to impedance of line.

$\overline{OI}$ = current in the circuit.

The motor terminal volts must be the resultant of the impressed voltage and the drop on the line. The diagram shows the conditions when the motor excitation has been raised until the current leads the voltage at the motor terminals. $\overline{OE_m}$ is greater than $\overline{OE}$.

The condition is one of resonance in so far as there is a periodic interchange of energy between the motor and the line. There are, however, important differences between the action of a super-excited synchronous motor and a condenser. The counter E.M.F. of the motor leads the current, it is true, but it is not proportional to it. It is, moreover, directly proportional to the frequency. The circuit has therefore no natural period corresponding to any given values of line inductance and motor excitation.

The resonant rise of potential depends on the angle θ_m and on $\overline{OE_s}$. The latter depends on the current. When the motor excitation is such that $\overline{OE_m}$ is in phase with the current, $\overline{OI}$ lags behind $\overline{OE}$, and $\overline{OE}$ is greater than $\overline{OE_m}$. As the motor field is increased, keeping the frequency and the generator volts constant, the current diminishes until it comes into phase with $\overline{OE}$, and $\overline{OE_m}$ increases. If the motor field is still further strengthened, $\overline{OI}$ begins to lead $\overline{OE}$, and to increase in amplitude. At the same time, both $\overline{OE_s}$ and $\overline{OE_m}$ are increased.

This process does not go on indefinitely, for the motor excitation reaches a point where, owing to increased losses, the angle θ becomes smaller.

If the motor field and the generator volts are kept constant while the frequency is increased, $\overline{OE_m}$ will increase as before, because both θ_m and $\overline{OE_s}$ are greater.

Method. — (*a*) Connect the synchronous motor in series with a generator through an inductance of suitable current-carrying capa-

city. Run the machines at half speed and adjust the motor field so that with normal generator field the armature current has a pronounced lead. Keeping the excitation of the motor and the generator volts unchanged, note the voltage across the motor terminals at different values of the frequency up to full speed.

N. B. — Keep generator voltage and motor field current constant. For each value of frequency the generator field will have to be adjusted to give the right terminal volts. Take ten readings.

Field Amps.	Arm. Amps.	Arm. Volts.	K.W.	Power Factor.	Volts at Generator.	Speed.	Remarks.

(*b*) Leave the connections the same as in (*a*). Run the machines at full speed, keeping the generator voltage and frequency constant. Note voltage across the motor for different values of the motor field current. Make the range of variation as great as possible without allowing the machine to drop out of step, or unduly heating the field coils at the upper limit.

N. B. — Keep generator terminal volts and frequency constant. Take ten readings.

Report. — Plot two curves:

(*a*) Motor terminal volts as ordinates, and frequency as abscissa.

(*b*) Motor terminal volts as ordinates, and motor field ampères as abscissæ. Draw the curves on separate sheets.

Polyphase Circuits and Transformations.

Experiment 26. — Balanced Two-phase System.

The object of this experiment is the study of the instantaneous values of the electrical quantities in a polyphase system and also to provide practice in balancing the load.

With full load on each phase and lagging currents, plot curves of current, E.M.F., power in each phase, and total power, assuming that the currents and E.M.F.'s are sine waves.

A balanced polyphase system is one in which the curve of total power is a straight line, for in such a system the total power is constant. In an unbalanced system the total power is pulsating with twice the frequency of the E.M.F.

Method. — Run a two-phase generator at rated speed and voltage. Draw an inductive load from each phase, in each of which a voltmeter, ammeter and wattmeter must be connected.

Adjust the values of inductance and resistance in the two circuits so as to balance the system as nearly as possible; if the system is exactly balanced, the volts, ampères and power factor of each phase will be the same. When a fair adjustment has been attained note the instrument readings.

Report. — The voltmeter and ammeter readings give effective values. If the volts and ampères are assumed to be sine waves, their maximum values will be found by multiplying the effective values by 1.41; their phase relations may be found by means of the wattmeter readings, since watts $= EI \cos \theta$.

Plot the volts and ampères of each phase as sine waves. The voltage curves of the two phases must be displaced in phase by 90°. Plot the watt curve for each phase from the products of the instantaneous values of volts and ampères. Plot the total power curve by adding the instantaneous values of the power curves of the two phases.

Plot all of the curves upon the same sheet of cross-section paper. Determine the ratio $\frac{\text{min. power}}{\text{max. power}}$. This ratio is called the "balance factor" of the system. If the system is perfectly balanced, the value of the balance factor will be unity.

Experiment 27. — Transformation from Two-phase to Three-phase by Means of Two Transformers.

It is possible to pass from one balanced polyphase system to another, by means of two transformers, no matter what the num-

ber of phases may be. Both primary and secondary systems must be balanced, or both must be unbalanced, for the transformers cannot store energy.

Method. — In Fig. 72 T_1 and T_2 represent the two transformers. The primary of each is connected to one phase of a two-phase generator G. The secondary of one of these transformers is connected to the middle point of the other secondary.

Fig. 71.

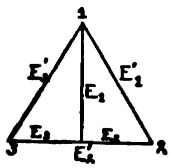
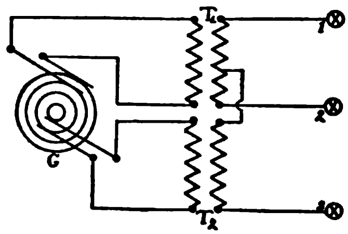
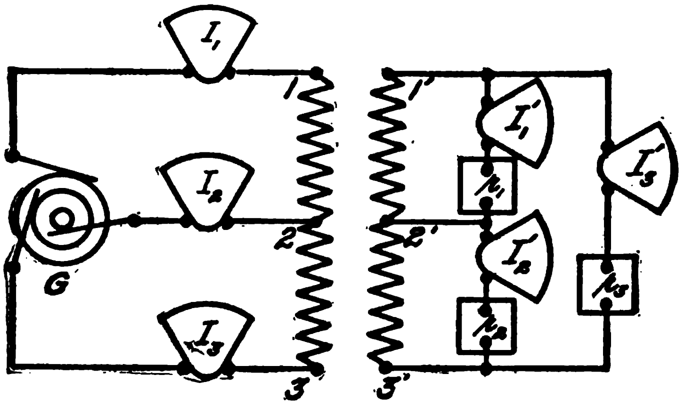


Fig. 72.



The secondary E.M.F.'s may be represented vectorially by E_1 and E_2', in Fig. 71. The points 1, 2 and 3 form the vertices of an equilateral triangle, and are therefore a source of three-phase

Fig. 73.



current. The triangle will be equilateral only on condition that the turns of the secondary winding are so proportioned that,

$$E_2' = E_1 \frac{2}{\sqrt{3}}.$$

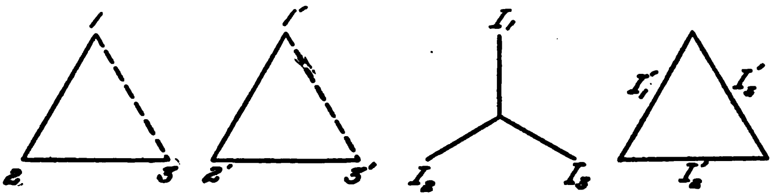
Connect the transformers as shown in Fig. 73 and measure the voltages E_1, E_2, E_3, E_1', E_2' and E_3'.

Report. — Construct a vector diagram, drawn to scale on cross-section paper, showing the phase relation and amplitude of the various E.M.F.'s as in Fig. 71.

Experiment 28. — Three-phase Δ with Two Transformers.

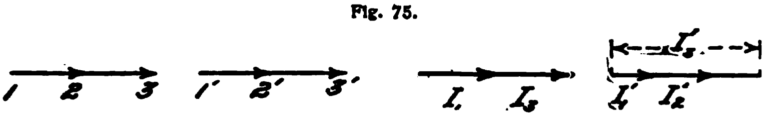
In three-phase transmission systems it is usual to obtain a lower voltage at the distributing end of the line by means of one three-phase transformer or three single-phase transformers, one

Fig. 74.



being connected in each phase. The same thing may be accomplished with two transformers. The secondary distributing system will then be Δ or Y, according to whether the secondary windings are connected so that their E.M.F.'s act in series with or in opposition to each other.

Fig. 75.



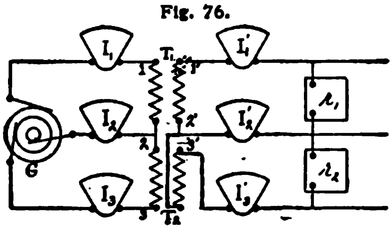
Method. — Connect the secondaries of the two transformers so that their E.M.F.'s act in series.

Whether they are acting in series may be determined by first connecting the two secondaries in circuit with each other through a voltmeter, the primary line, at 2 in Fig. 73, being temporarily open. If the instrument deflects, the E.M.F.'s are acting in series,

and the secondaries have been correctly connected. If the voltmeter shows no deflection, it is because the voltages are in opposition, and the connections of one secondary must then be reversed.

Adjust r_1, r_2 and r_3 so as to draw equal currents from the transformers. Note the values of the primary and secondary delta voltages and ammeter readings as shown in Fig. 73.

Fig. 76.



After this has been done, open the line wire at 2, keeping the other connections unchanged. Note the currents and the voltages shown in Fig. 73.* It will be seen that the system is now single phase, the resistances r_1 and r_2 in series with each other are in parallel with r_3 across the voltage 1′–3′.

Report. — Construct vector diagrams similar to those of Figs. 74 and 75, using the actual readings obtained. Draw these diagrams to scale on cross-section paper. Place the diagrams of this experiment and those of Experiment 29 on the

Experiment 29. — Three-phase Y with two transformers.

Method. — Connect the apparatus as shown in Fig. 76, arranging the secondaries so that their E.M.F.'s are in opposition, and not in series as in Experiment 28. Adjust r_1 and r_2 so as to make the currents I_1' and I_3' equal. Note the primary and secondary line currents, the primary delta voltages and the secondary voltages 1′–2′, 2′–3′ and 1′–3′.

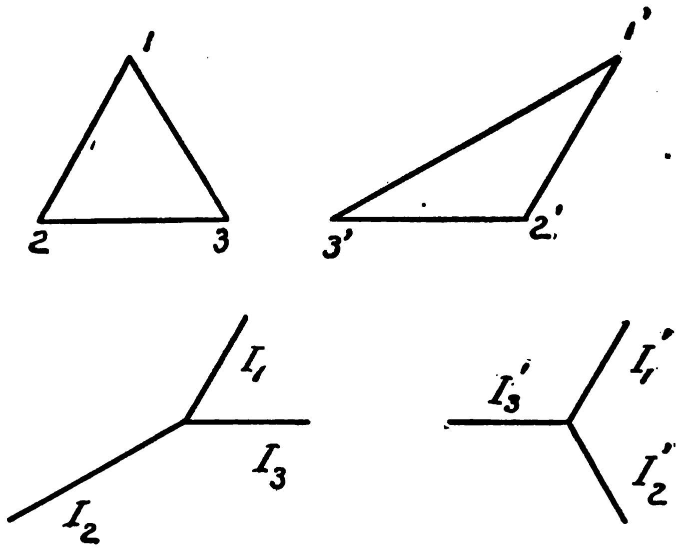
The secondary system is an unsymmetrical balanced three-phase Y. One leg of the Y is missing. It is sometimes called the inverted three-phase system.

Break the primary line wire No. 2, so as to make I_2 equal to zero, and again note the ammeter and voltmeter readings.

*In Fig. 74 and 75, the points 1, 2, 3 correspond to the points 1, 2 and 3 of Fig. 73. The same is also true of the points 1′, 2′ and 3′ in these figures.

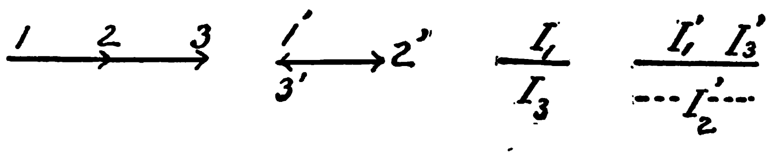
Report. — Construct diagrams corresponding to Figs. 77 and 78, using the actual ammeter and voltmeter readings. Draw these diagrams on the same sheet of cross-section paper as those of Experiment 28.

Fig. 77.



It will be found that breaking the middle primary wire brings points 1′ and 3′ to the same potential. The current I_2' then becomes equal to the sum of I_1' and I_3' as shown in Fig. 78.

Fig. 78.



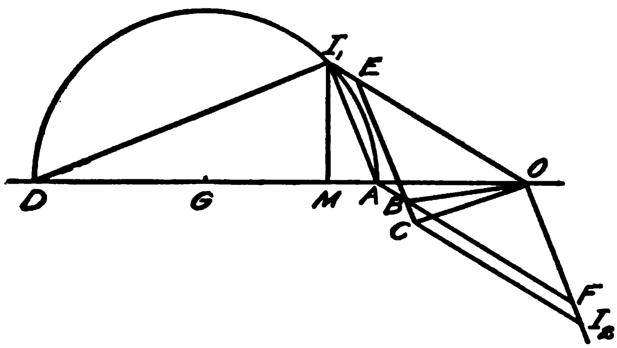
Test of an Induction Motor.

An induction motor resembles a direct current shunt motor in that the stator field at any one load makes a constant angle with that due to the rotor. The difference lies in the fact that in the induction motor these two fields rotate at synchronous speed

whereas in the shunt motor they are both stationary in space. Also, in the induction motor the current is not led into the rotor by means of brushes and commutator, but is induced in the rotor winding by the relative rotation of the stator field. This transformer action is a characteristic feature of the induction motor, the machine being really a transformer with a movable secondary, and consequently an air gap in the magnetic circuit, which gives rise to a considerable leakage flux.

If the primary impressed E.M.F., E_1, and the frequency are constant, and the resistance of the primary circuit is negligible, the flux cutting the primary turns must always be the same, since the counter E.M.F. due to its rate of change must be always practically equal and opposite to the constant impressed E.M.F. Also, this condition must continue to hold in spite of the magnetic leakage which increases with the load; the primary flux, therefore, is composed of two portions, the lines which link with the

Fig. 79.



primary turns alone, and those that are mutual to both primary and secondary turns. This may be expressed by the equation

$$\phi = \phi_a + \phi_s,$$

in which ϕ_s is the stray field linked with the primary turns alone and in phase with the primary current, while ϕ_a is in phase with the resultant of both primary and secondary currents.

The approximate diagram of the induction motor on constant potential circuit is shown in Fig. 79. $\overline{OA}$ is the total primary flux ϕ, and $\overline{OI_1}$ is the primary, or stator, current which produces the primary leakage flux ϕ_s represented by the line $\overline{AB}$. ϕ_s is in phase with $\overline{OI_1}$ because the leakage paths are mainly through the air, and it is well known that a magnetic flux in an air path is in phase with the magnetomotive force producing it. Furthermore, the permeance of these paths is very nearly constant throughout a wide range of flux density, so that the length $\overline{AB}$ may be taken as directly proportional to $\overline{OI_1}$. The actual M.M.F. producing the leakage flux ϕ_s may be represented by the length $\overline{EI_1}$, and the length $\overline{OE}$ may be taken as the primary M.M.F. which acts to produce a flux linking with the secondary turns.

The secondary current is given by the line $\overline{OI_2}$ and the length $\overline{FI_2}$ is the M.M.F. which produces the secondary leakage flux $\overline{BC}$. The total flux included by the secondary winding is represented by the line $\overline{OC}$ which leads the current by 90°, because the latter is due to its rate of change.

The length $\overline{OF}$ is the secondary M.M.F. which tends to produce a flux cutting the primary turns.

The mutual flux, ϕ_a, is represented by the line $\overline{OB}$ being due to the combined action of M.M.F.'s $\overline{OE}$ and $\overline{OF}$.

It can be shown that the point I_1 travels on a semicircle whose diameter is $\overline{AD}$, and that $\overline{OD}$ is approximately equal to the current at standstill. $\overline{OA}$ similarly represents the no load current, neglecting losses, and I_1M represents the power supplied to the motor.

This diagram has been so fully discussed in the literature of the induction motor that it is not thought necessary to reproduce the proof of it here. The simple form shown in Fig. 81 is useful because it affords an easy means of grasping the main electrical and magnetic characteristics of the operation of an induction motor.

As the load comes on and the slip consequently increases, the vector $\overline{OI_1}$ is altered so that its extremity travels around the

circumference of the semicircle AI_1D, and the resulting relative variations of the other vectors can be readily observed. The diagram shows the following properties:

(*a*) The locus of the point I_1 is a semicircle because the angle DI_1A is a right angle.

(*b*) The primary and secondary currents, represented by the lines $\overline{OI_1}$ and $\overline{OI_2}$ increase with the load.

(*c*) The useful flux $\phi_a = \overline{OB}$ decreases with the load.

(*d*) The stray field $\phi_s = \overline{AB}$ increases with the load.

The torque of the motor depends on the product $I_2\phi_a$, where I_2 is the rotor current.

As the load comes on it is necessary that this product shall increase. This is accomplished by an increase in the slip, which increases I_2 because the secondary E.M.F. and therefore I_2 are proportional to the slip.

At first, as shown in the diagram, I_2 increases more rapidly than ϕ_a diminishes, so that upon the whole, $I_2\phi_a$ becomes greater, and the torque increases with the slip.

As the slip goes on increasing, however, a point is reached at which the product $I_2\phi_a$ ceases to increase. If a still heavier load is applied, the motor will stop. This is due to the fact that I_2 has become very great, and has blown out the useful flux to such an extent that there is insufficient torque. It is on this account that at starting, when the slip is 100 per cent., it is usually necessary to insert a starting resistance in the secondary circuit to cut down I_2.

Both I_2 and ϕ_a are proportional to E_1. It follows that the torque of the motor varies, within limits, as the square of the impressed volts.

From the above discussion of the action of the motor, it appears that:

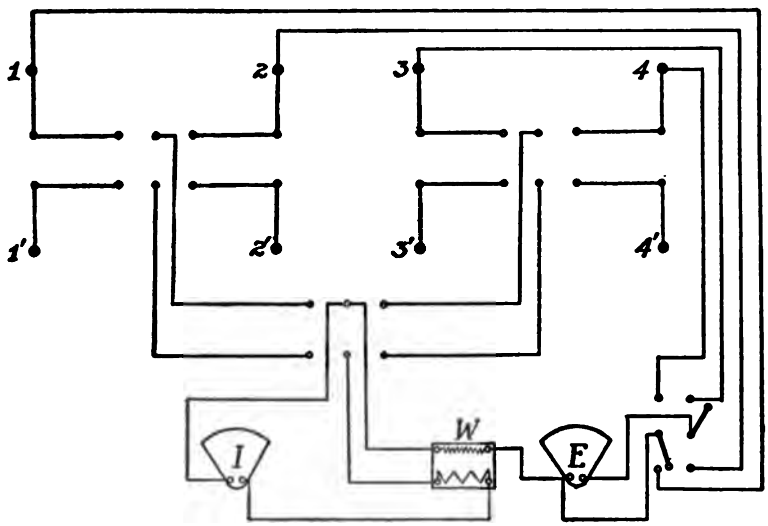
(*a*) Unless specially designed, the motor will lose its torque and stop if the load causes the slip to increase beyond a certain maximum value. By inserting a suitable resistance in the rotor circuit, however, it is possible to obtain maximum torque at any desired value of the slip.

(*b*) The motor is very sensitive to a variation in the voltge, and is liable to lie down when heavily loaded, if the voltage is allowed to drop below a certain point which is a function of the design of the machine.

The design of an induction motor involves to a great extent the same principles which enter into the theory and construction of a static transformer; the regulation of the motor depends upon the impedance drop in the primary and secondary windings, while the temperature rise is due to hysteresis and eddy current losses in addition to copper losses and friction.

The impedance drops in the windings are equal to the rate of change of the leakage fluxes in the primary and secondary circuits represented in Fig. 79 by the lines $\overline{AB}$ and $\overline{BC}$ respectively.

Fig. 80.

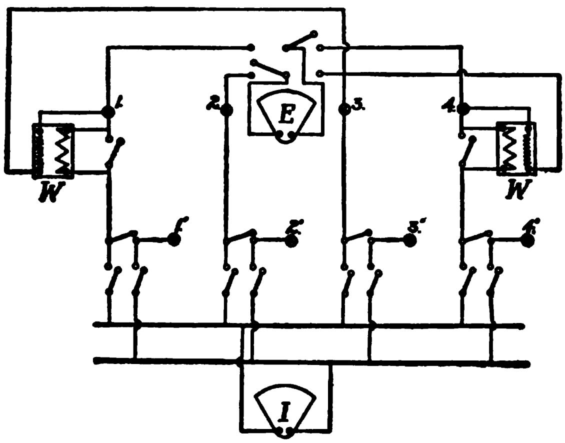


In testing polyphase machines it is convenient to make use of specially designed switchboards similar to those shown in Figs. 80 and 81. Many such arrangements can be devised, the object being to read the three phases as quickly as possible with the same set of instruments.

The leads coming from the source of power are connected to the binding posts, 1, 2, 3 and 4 and the circuits after passing through the switches and instruments pass from binding posts 1′, 2′, 3′ and 4′ to the machine under test. For two phase, all four connections are used, and any three for three phase. The single pole switch between each corresponding pair of terminals as 1 and 1′, when closed, allows the current to pass directly to the machine without passing through the instruments.

In order to read any phase as 1, Fig. 80, the lower and left hand d. p. d. t. switches are thrown over to the left and the single pole switch between terminals 1 and 1′ is opened. The current of phase 1 then passes through the ammeter and wattmeter.

Fig. 81.

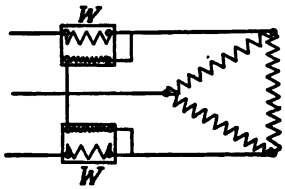


The single pole switches protect the instruments, and that of each phase is kept closed unless it is desired to read the current.

In a two-phase system the total power is the sum of the watts of both phases, the current coil of the wattmeter being connected in one wire of each phase in the ordinary manner. In a three-phase system the total power is the sum of two wattmeter readings, the instruments being connected as shown in Fig. 82.

In a similar manner, the total power of an n-phase system is determined by $(n - 1)$ wattmeter readings, one terminal of the pressure coil being constantly connected to the same phase, the other terminal being in succession connected to each of the other phases into which the current coil is at the same time inserted.

Fig. 82.



Care should be taken to insert the current coil of the wattmeter in all the phases in the same sense. In a three-phase system one of the wattmeter readings will be negative if the current in the corresponding phase lags more than 60 degrees. Therefore, if the needle deflects the wrong way, reverse the terminals of the current or pressure coil, and subtract the reading thus obtained from the other positive reading.

Experiment 30. — Determination of Impedance, Starting Torque, Copper and Load Losses and Saturation Curve at Standstill.

Method. — The instruments used in this test are a voltmeter ammeter and wattmeter, connected by means of the switchboard already described so that all necessary measurements can be made in the different phases. A brake should be placed on the pulley of the motor and clamped rigidly to it, so that the balance will indicate the starting torque corresponding to any set of instrument readings. Beginning with a very small impressed voltage take readings of volts and ampères per phase, total watts and starting torque for successive values of the impressed volts, carrying the test up to the heating limit of the machine. The majority of induction motors will readily stand a 200 per cent. current overload for a short time. When dealing with the larger currents it is advisable to let the motor run free for a short time between readings in order to cool it.

In addition to the methods described, the starting torque of small and medium sized motors may be determined in the following way.

With no current in the stator, clamp the brake tightly to the

pulley, and connect a spring balance of suitable capacity to measure the starting torque to the end of the lever arm. Suspend a weight W on the lever arm, heavy enough to overcome the static friction if unopposed by any other force. Keeping the spring balance vertical, slowly pull up the lever arm by means of it and note the reading at the instant when the lever arm is passing through the horizontal position; the reading will be

$$W_1' = W + f$$

in which f is the friction reaction.

Keeping the balance still vertical, allow the weight W to drag the lever arm down again, and note the reading as before in passing through the horizontal position. This second reading will be

$$W_1'' = W - f.$$

Therefore by subtraction, we obtain the value of the reaction due to friction,

$$f = \frac{W_1' - W_1''}{2}.$$

Close the line switches, and bring the voltage up to the desired value by gradually increasing the alternator field current; then, by first raising and afterwards lowering the lever arm by means of the spring balance as already described, obtain a second set of readings which will be

$$W_2'' = W - f + \mathbf{T},$$

where **T** is the starting torque.

By adding these two equations we have

$$\mathbf{T} = \frac{W_2' + W_2''}{2} - W.$$

Since the value of f was determined from the first set of readings, **T** may be calculated directly from this equation.

A third method of measuring the losses is by noting the rate of retardation of the rotor after the power is cut off. This is done first with no load, and then with a small constant torque.

Since the power developed against the retarding torque $\mathbf{T}$ is equal to the time rate of change of the kinetic energy, and since the power absorbed by the retarding torque is $\mathbf{T} \times (d\theta/dt)$, we may write

$$\mathbf{T} = I\frac{d^2\theta}{dt^2} = K\frac{dN}{dt},$$

in which N is the tachometer reading.

As the machine slows down, about six readings of speed should be taken at observed intervals of time, and these readings should be plotted as ordinates with respect to time as abscissa.

Having performed this operation, bring the machine again up to the same initial speed and apply a constant known torque T' to the pulley, disconnect the driving power and note the speed at observed intervals of time as before. In this case

$$\mathbf{T} + \mathbf{T}' = K\left(\frac{dN}{dt}\right)'.$$

Plot the values of N with respect to time as before, on the same sheet and to the same scale as the previous curve.

Combining the two equations K disappears, and we have

$$\mathbf{T} = \frac{\mathbf{T}'\dfrac{dN}{dt}}{\left(\dfrac{dN}{dt}\right)' - \dfrac{dN}{dt}}.$$

For any desired value of speed, determine dN/dt and $(dN/dt)'$ from the curves, substitute in the last equation and calculate T.

The friction losses in H.P. at any speed may be found from the expression

$$W = \frac{2\pi \mathbf{T} N}{33000}$$

Report. — Calculate the impedance of one leg of the winding by dividing the voltage across it by the current traversing it. Bear in mind that in testing a three phase machine the voltmeter and ammeter give always the line volts and amperes; so that if E and I are the instrument readings, the impedance per circuit is $Z = E/\sqrt{3}I$ for a Y wound motor, and $Z = \sqrt{3}E/I$ for a Δ wound motor. The only way of finding out whether a machine is wound Δ or Y is by examining the winding; no resistance test or other measurement will ascertain this.

With ampères as abscissæ, plot the following curves on the same sheet of cross section paper.

(*a*) *Impressed Volts.* — Since the induction is practically proportional to the voltage this is really a saturation curve.

(*b*) *Total Watts Input.*— This curve will include both the true ohmic losses and those due to the leakage magnetic flux, which are practically the load losses, there being almost no mutual flux at standstill with a short-circuited low resistance rotor winding.

(*c*) *Total I^2R Losses.*

(*d*) *Starting Torque.*

Take ten sets of readings.

It often will be found that the starting torque may sometimes depend on the angular position of the rotor. To investigate this, a series of readings at the same impressed voltage should be

Type of Winding- Y, Δ
Res. per phase- R-

Amperes			Volts			K.W.					
1.	2.	3	1-2.	1-3.	2-3.	1-3.	1-2.	Starting Torque	I^2R.	Z.	Remarks

obtained with the rotor in several different positions within the angle subtended by a pair of poles.

Calculate the friction loss at rated speed.

In this test, as in the following, readings should be taken of

the rotor currents if the motor is fitted with collector rings and brushes.

Experiment 31. — With the Motor Running Free, Determine the Friction and Core Losses, together with the No Load Saturation Curve.

Method. — Beginning with as high a voltage as the design of the motor will permit, take a series of readings of total watts, volts and ampères per phase and speed, at successively lower values of the impressed volts until the machine falls out of step.

The connections for this test are the same as for Experiment 30, the range of some of the instruments only being different.

When running free at the rated voltage the power supplied to the machine is equal to the core and friction losses together with a small I^2R loss which can readily be subtracted if it is sufficient to make this worth while; when, however, the voltage is lowered so that the motor is on the point of stopping, the watts supplied minus the I^2R loss are practically equal to the friction losses at this speed. The reason for this is that the core losses diminish more rapidly than the voltage decreases, and are very small when there is still E.M.F. enough to keep the rotor in motion. The friction loss at any speed can therefore be approximately calculated from this reading at low voltage by assuming that it is proportional to the speed. The friction losses may then be subtracted from the total stray power losses to find the core loss.

Amperes			Volts			K.W.		Core Losses					
1.	2.	3.	1-2.	1-3.	2-3.	1-2.	1-3.	Rotor	Stator	Friction Losses.	Speed in % of Synchronism	Power Factor.	Remarks.

If the rotor is fitted with collector rings, the core losses may be obtained directly at any speed by opening the rotor circuits

and noting the instrument readings before the machine has time to slow down.

Take ten sets of readings.

Report. — With impressed volts as abscissæ, determine the following curves, plotting them all on the same sheet:

(*a*) Ampères.

(*b*) Speed in per cent. of synchronism.

(*c*) Total watts input.

(*d*) Power factor.

From these curves find the core loss and the friction loss by the method described.

Calculate the power factor of a three phase motor by the relation

$$\cos\theta = \frac{\text{total watts}}{\sqrt{3}EI}$$

where E and I are the average volts and amperes per phase.

If the machine is two phase, omit the factor $\sqrt{3}$ and divide by 2.

As the load comes on, the stator iron losses diminish due to the fact that the increased resistance drop cuts down the primary counter E.M.F. of self-induction, and consequently the primary flux; the rotor core losses, on the other hand, increase with the load on account of the greater frequency, therefore the total iron losses of the motor remain very nearly constant between no load and full load.

Experiment 32. — Determination of the Following Curves:

(*a*) Commercial efficiency by noting output and input.

(*b*) Commercial efficiency by calculation.

(*c*) Apparent efficiency.

(*d*) Current per phase.

(*e*) Speed in per cent. of synchronism.

(*f*) Torque.

(*g*) Power factor.

Curves (*a*), (*b*) and (*c*) are to be plotted on one sheet with K. W. output as abscissa. Similarly curves (*d*), (*e*), (*f*) and (*g*), with K. W. output as abscissa.

Method.—If the polyphase system is perfectly symmetrical it may be only necessary to take readings in one phase; in practice, however, this is rarely the case, and the readings are to be taken in the same manner and with the same connections as in Experiments 30 and 31.

Load the motor by means of a brake or by connecting it to a generator whose losses are known. The output of the motor will then be equal to that of the generator plus its losses, the latter being known. If a belt is used the belt losses and friction of the generator are assumed to be independent of the load; they may be determined by noting the power taken by the motor when driving the generator with its field circuit open, and subtracting the power taken by the motor when running free with the belt off. This result should be corroborated by the determination of the counter-torque. This is made by operating the generator as a motor, with the induction motor belted to it but disconnected from the A.C. mains.

In order to determine the required curves note the readings of ampères and volts per phase, total watts input and output and the speed at ten successive values of the output from zero to full load.

It is very desirable to measure the slip directly, when possible, by some stroboscopic method. It is then only necessary to take the speed of the generator.

A disc with black and white sectors, one black sector for each pair of poles, is mounted on the motor shaft. The light of an arc lamp supplied with a current of the generator frequency is made to illuminate the disc, and the black sectors will appear to revolve like the spokes of a wheel in the direction of the slip. The numerical value of this quantity is

$$S = \frac{Np}{60f},$$

where N is the apparent number of R.P.M. of the disc, p is the number of pairs of poles and f is the alternator frequency.

N. B. — Great care must be taken throughout the test to keep the impressed volts and frequency constant.

Report. —

(*a*)
$$\text{Commercial efficiency} = \frac{\text{output}}{\text{input}}.$$

The input is obtained by adding the two wattmeter readings. The output is equal to the belt losses plus the output and losses of the generator, unless a brake is used to load the motor.

(*b*)
$$\text{Commercial efficiency} = \frac{\text{input-losses}}{\text{input}}.$$

The losses are:

(1) The copper losses and load losses obtained from the wattmeter readings of Experiment 30.

In the case of a three phase motor, the current corresponding to any input is

$$I = \frac{\text{total watts input}}{\sqrt{3}E \times \text{power factor}},$$

where the power factor is obtained from a curve which has been assumed from previous experience, or calculated from the resistances and reactances of the motor. For a two phase motor, divide by 2 instead of $\sqrt{3}$. The same thing is true of the power factor calculation (*g*).

Efficiency by Experiment.

Amperes.			Volts.			K.W.		Power Factor.	Speed.	D.C. Generator.				Efficiency.	Remarks.
1.	2.	3.	1-2.	1-3.	2-3.	1-2.	1-3.			Volts.	Amps.	Losses.	K.W. Motor Load.		

(2) The core losses, friction and windage, assumed to be constant. They are taken from the results of Experiment 31. The magnetizing current, together with the friction loss component of current, are assumed to be constant and are also taken from Experiment 31.

(*c*) $\text{Apparent efficiency} = \dfrac{\text{output}}{\text{volt-ampères input} \times \sqrt{3}}$. If there

are slight differences between the volts and ampères of the different phases, the average values may be used.

(*d*) Curve of current in each phase.

(*e*) Speed in per cent. of synchronism; the synchronous speed is equal to the frequency multiplied by 60 divided by the number of pairs of poles.

(*f*) $$\text{Torque} = \frac{\text{K. W. output} \times 33{,}000}{\text{revs. per min.} \times 2\pi \times .746}.$$

Unless a brake is used, the "output" is the load of the generator together with its losses and those due to the belt.

(*g*) $$\text{Power factor} = \frac{\text{watts input}}{\text{volt-ampères input} \times \sqrt{3}}.$$

Efficiency by Calculation.

Frequency- *Exciting Current-* *Impressed Volts-*
No. of Poles- *Magnetizing " -*

Output in K.W.	Iron Losses.	Copper Loss + Load Loss.	Friction Losses.	Energy Component of Current per Phase.	Total Current per Phase.	Speed in % of Synchronism.	Input.	Power Factor.	Efficiency.

ROTARY CONVERTERS.

I. RUNNING FROM THE A.C. END.

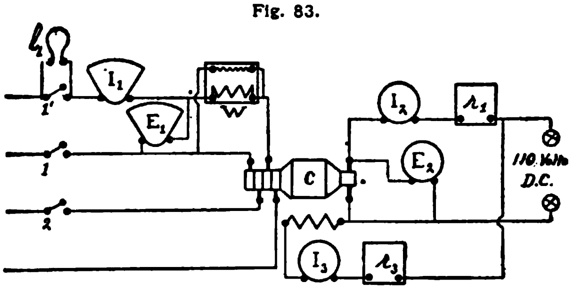
Experiment 33. — Various Methods of Synchronizing a Polyphase Converter. Determine the Efficiency and External Characteristic Curves at the D.C. End. (a) Using the Two-Phase Converter; (b) Using the Same Machine Running Single Phase.

In a direct-current motor-dynamo the armature reaction is almost entirely absent. Except for that portion of the current which overcomes the losses of the motor the effect of the ampères input is completely neutralized by the ampères output. In a converter the same thing is true at unity power factor, and the armature reaction is due to the component of the current which produces the rotation of the armature.

In any particular inductor the current entering the A.C. end is a sine wave. That delivered at the D.C. end must also pass through this same conductor. It will be of opposite sign to the current from the A.C. end; it will also be alternating with respect to the conductor. Instead of being a sine function, however, its value is constant throughout each half period. It is for this reason that the alternating current supplied is not by any means completely neutralized by the direct current output as far as the ohmic losses are concerned. As the number of phases increases, the A.C. and D.C. ampères neutralize each other more completely, and the I^2R losses become less; consequently the efficiency of a polyphase rotary increases with the number of phases.

A polyphase synchronous motor has the advantage of being easier to synchronize than a single-phase machine, owing to the fact that it acts more or less strongly as an induction motor due to the eddy currents developed in the pole pieces by the rotary field.

Fig. 83.



This is a quality which is useful in starting the machines and running them in parallel.

Method.—Before determining the curves of efficiency and terminal volts, synchronize the converter by the following methods and note the action of the machine.

1. Start the converter as a direct-current motor from a constant potential circuit. When the machine is in step as shown by the synchronizing lamp l_1, switch 1' may be closed, Fig. 83. Switches 1 and 2 should be closed at the same time, provided the connec-

tions have been arranged so that this second phase will not tend to reverse the direction of rotation. If synchronizing lamps are connected in both phases, the proper condition will be shown by the lamps of both phases being black at the same instant.

2. Open the field circuit of the converter, and start as an induction motor by lowering the voltage of the generator in order to prevent the current from being excessive. The rotary will gradually increase in speed until it finally slips into synchronism, which can readily be observed by the sudden diminution in current. The machine is then running as a synchronous motor drawing from the line the energy current required to produce rotation, and a lagging current sufficient to magnetize the field. The D.C. field circuit may now be closed and the excitation, beginning with a small value, gradually increased. During this process the armature current should still further decrease; if the reverse is the case it is evident that the rotary did not swing into synchronism in the right angular position, and it is necessary to reverse the field current. The excitation should now be adjusted for minimum armature current, this being the proper condition for operation. If it is inconvenient to reverse the excitation it is possible to make the rotary slip a pole by increasing the field strength until the armature is forced into a position of synchronism differing in phase by 180° from the former one. This operation, however, will cause the machine to draw a very large current from the line.

3. Start the converter by bringing it from standstill to full speed at the same time with the generator. The switches connecting the armatures of the machines must be closed, while both generator and rotary are given their normal field excitation. During the process of starting by this method the machines are in synchronism throughout the entire operation, and the current taken from the line is small.

4. Bring the converter to a speed slightly greater than synchronism by running it as a direct current motor, the A.C. switches being open. The synchronizing device will be sufficient to show

when the proper speed has been reached. Disconnect from the D.C. mains by first opening the armature circuit and then that of the field; then quickly close the A.C. armature switches. The converter will drop into synchronism as it slows down, and the current taken from the line will not be excessive. The field circuit should now be closed in the same way as in method (2) beginning with a very small excitation, as in both these methods it is impossible to foretell which way the rotary will swing into synchronism.

(*a*) Determination of the efficiency and external characteristic curves, running as a two-phase converter.

The field current must be kept constant at the value which makes the current input a minimum at no-load. Run the generator so that it gives the rated frequency of the converter.

The machines may be loaded by means of a resistance connected across the terminals of the D.C. end. It is more economical, when possible, to feed into the D.C. power circuit if the potential of the circuit is lower than that of the converter. The method of doing this is shown in Fig. 83. Vary the load by adjusting r_1. Take eight readings of input and output, carrying the test from no-load to full load.

A convenient method of testing rotary converters is to handle them in pairs, the D.C. ends being in parallel with the source of power, and the A.C. ends connected in series with each other

Amperes.			Volts.			K.W.		Power Factor.	Speed.	D.C. End.			Efficiency.	Remarks.
1.	2.	3.	1-2.	1-3.	2-3.	1-2.	1-3.			Amps.	Volts.	K.W.		

through some form of electromagnetic potential regulator whose function is to determine the amount of energy transmitted from one machine to the other. In this way one rotary converter drives the other as an inverted rotary, the losses being supplied from the line.

(*b*) Determination of the efficiency and external characteristic curves running as a single-phase converter.

Open one of the two phases, and the rotary will continue to run single-phase. Note the readings of input and output at the same loads as in (*a*).

N. B. — Keep converter field current, frequency and impressed volts constant. Take eight sets of readings in both (*a*) and (*b*).

Report. — Plot the efficiency curves of (*a*) and (*b*) on the same sheet, taking the values of efficiency in per cent. as ordinates, and of horse-power output as abscissæ.

Plot the readings of the voltmeter at the D.C. end in (*a*) and (*b*) as ordinates, with respect to ampères output as abscissæ. These external characteristics curves are both to be plotted on the same sheet.

Experiment 34. — (a) At Full Load Determine the Relation Between the D.C. Volts and Field Current. (b) Insert an Equal Inductance in Each Phase, and Determine the Same Curve.

In a rotary converter the voltage at the D.C. end is the same as the counter E.M.F., except for the *IR* drop. The counter E.M.F., however, is proportional to the impressed alternating volts except for the drop due to armature impedance. Varying the field of a rotary converter has very little effect, since the wattless currents drawn from the line always tend to counteract the change in the field current, so that a counter E.M.F. is maintained equal to the vectorial difference between the impressed volts and the impedance drop. It is therefore difficult to regulate the D.C. voltage of a rotary except through a very small range of variation, and any such regulation will involve a heavy wattless current.

This is not, however, the case if there is inductance between the converter and the A.C. generator (see Exp. 25). The voltage at the A.C. and D.C. ends can then be raised by means of the field current owing to the fact that the leading current taken by the A.C. end causes a resonant rise of potential. This fact is brought out in this experiment.

Method (*a*).—With the same connections as in Fig. 85, at full-load direct-current output, vary the field of the converter, and note the D.C. voltage. (*b*) Insert an equal inductance in each phase, and note the voltmeter readings at the same field strength. Tabulate the readings as in Experiment 33, substituting "Field Ampères" for "efficiency."

N. B.—Keep constant the generator terminal volts, the frequency and the direct-current ampères. Take four readings in each case.

Report. — Plot two curves (*a*) and (*b*) on the same sheet with volts at the D.C. end as ordinates and field ampères as abscissæ.

II. Running from the D.C. End, The Inverted Rotary Converter.

Experiment 35.—At Full Load, Non-Inductive, Determine the Curves of Speed and A.C. Voltage in Relation to the Field Current.

The direct current end of the machine is now the motor, and all the conditions with regard to speed regulation are the same as in the case of a direct current motor; the counter E.M.F. will always be equal to the impressed voltage minus the resistance drop in the armature, and the speed will depend upon the field strength. It will therefore be found in carrying out this test that as the field current is increased the speed will drop, but the alternating voltage will remain almost constant.

Method. — Make the connections as in Fig. 84, running the machine single-phase for the sake of convenience. Adjust the load resistance so as to draw full-load current, and leave it unchanged throughout. Vary the field current through as wide a range as may be possible with safety and note the values of the voltage at the A.C. end and the speed. Tabulate the readings as in Experiment 34.

N. B. — Keep the impressed volts at the direct-current end constant. Take four readings.

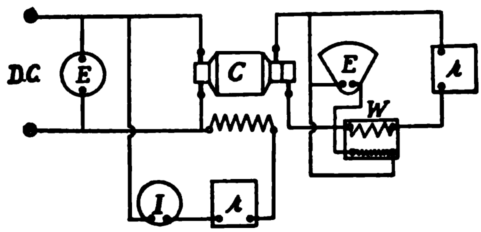
Report. — Plot two curves on the same sheet; one with volts

at the A.C. end, and one with speed in revs. per sec. as ordinates. Use the values of field current as abscissæ for both curves.

Experiment 36.—With Lagging Current, Vary the Output While Keeping the Power Factor Approximately Constant. Determine a Curve with Speed as Ordinate and Current Output as Abscissa.

The effect of a lagging current upon the field of an A.C. generator was discussed on pages 122–123. Its action is to blow out the lines of force far more than if the current were in phase with the E.M.F. Increasing the output with a lagging current weakens the field. This, in an inverted rotary converter, causes the speed to rise. Since this will still further increase the lag, owing to the increased reactance, the converter is liable to run away.

Fig. 84.



Method.—Use the connections shown in Fig. 86, except that an inductive load must be substituted for the resistance used in Experiment 35. Keeping the power factor constant by adjusting the inductance and resistance of the circuit, increase the current output, and note the values of the speed. Tabulate the readings as in Experiment 34.

N. B.—Keep the converter field and impressed volts constant. Take four readings.

Report.—Plot a curve having speed as ordinate, and current output at the A.C. end as abscissa.

THE INDUCTION GENERATOR.

This machine consists of an induction motor the rotor of which is driven by mechanical power at a speed greater than synchronism, the counter E.M.F. of the induction motor becoming thereby

a generator voltage much in the same way as when a shunt motor is driven at sufficient speed to make it feed back into the line. When running as an induction motor the field excitation of the stator is maintained by a component of current which leads the counter E.M.F. of the stator by 90° ; consequently when the machine becomes a generator it will not maintain its voltage unless it develops a sufficient component of current leading the induced voltage by 90°. An induction generator will therefore not be able to supply lamps or induction motors unless it furnishes at the same time sufficient leading current not only to magnetize the field but also to counteract any lagging component of the load current.

This difficulty may be met by putting condensers in parallel with the induction machine, but the more usual method is to connect one or more synchronous motors in parallel with the load.

When a synchronous motor is used to excite an induction generator it must be first brought up to the proper speed by some separate source of power. Before building up the field excitation, the switches connecting motor and generator should be closed, and then the voltage of both machines may be built up by increasing the field current of the synchronous machine. There can be no appreciable transference of energy during this process as long as the speeds are the same.

On reaching the desired voltage the driving power may be disconnected from the synchronous machine which will then continue to run as a motor, the induced voltage of the induction generator dropping until it is sufficiently below that of the synchronous motor for the leading current to flow, which is required to maintain the generator field.

The voltage of an induction generator may be most conveniently increased by increasing the field excitation of the synchronous motor, thereby increasing the leading current, and consequently the field strength of the generator. The stronger field of the synchronous motor increases the excitation of the induction generator by drawing a greater leading current from it,

thereby raising the terminal voltage and consequently increasing the torque of the synchronous motor. This accelerates the latter, and increases the frequency of the alternating current supplied by the generator; the result of varying the field current of the synchronous motor is, therefore, to alter correspondingly both the voltage and the frequency of the system.

Increasing the speed of the generator has the effect of causing the rotor to cut more lines of force. This has the effect of raising the voltage just as in a direct current shunt generator; at the same time more current is supplied to the synchronous motor; this increases its turning moment, causing it to run at higher speed, thereby increasing the frequency of the current supplied by the alternator. The effect of a change in the speed of an induction generator is, therefore, to alter both the voltage and the frequency of the system correspondingly.

When both induction and synchronous machines are driven by mechanical power either machine, by increasing the speed of its prime mover, may be made to drive the other as a motor. This principle is used in a variety of "feeding back" methods for testing combinations of machines.

Experiment 37. — Operation of an Induction Generator. Determination of its External Characteristic.

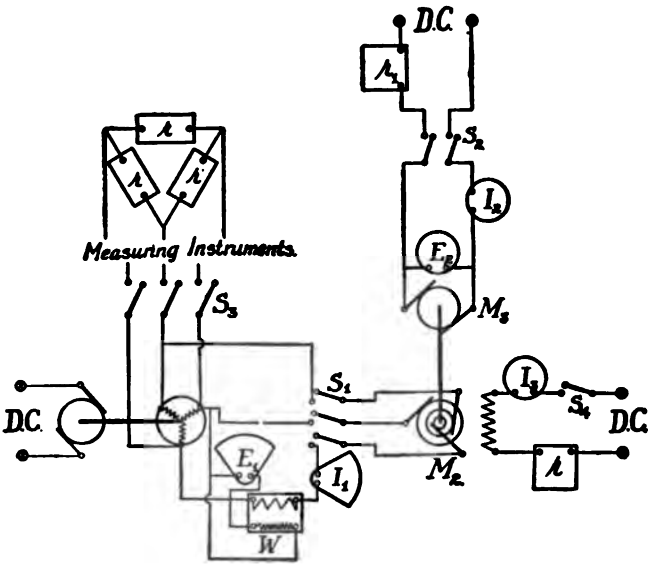
Method. — Make the connection as shown in Fig. 85, the switches S_1, S_3 and S_4 being open, and switch S_2 closed so as to connect the motor M_3 to the D.C. mains. Bring both the induction and the synchronous machines to the same frequency, being a little above that at which the test is to be carried on, and close switch S_1. Then, beginning with a small field current, I_3, gradually raise the voltage to the desired value, and open switch S_2, the load switch S_3 being open.

The synchronous machine will now be running as a motor driving the D.C. machine M_3. The frequency and voltage will be slightly lower than before opening S_2 due to the fact that current must now be supplied by the induction generator to operate M_2. The internal impedance drop due to this current naturally

lowers the voltage at the generator terminals, and the speed of M_2 falls correspondingly until its induced voltage is just enough above that of the generator to maintain the leading current required for the excitation of the latter, and so that at the same time it will be supplied with the energy component of current required to drive it. Causing the induction generator to supply a load, as by closing S_3, will produce the same result.

Adjust the speed of the generator and the excitation of the motor until the desired frequency and voltage are attained. Close

Fig. 85.



switch S_3 and regulate the load by means of the adjustable resistances. Keeping the system balanced take six sets of readings between no load and full load with the generator speed and motor excitation constant. Note the volts and amperes of the load, the amperes and watts supplied to the motor M_2, and its speed.

Report. — With the ampères in the load circuit as abscissæ construct the curves of the volts, speed, current and watts motor, putting them all on the same curve sheet.

Synchronous Motor										Load.					Generat. Speed	Remarks
Speed	Amperes			Volts.			K.W.		Field Amps.	Amperes			K.W.			
	1	2	3	1-2	1-3	2-3	1-2	1-3		1	2	3	1-2	1-3		

Experiment 38. — Variation of Motor Field Current at Constant Generator Speed.

Leave the connections as in the last experiment, except that the switches S_2 and S_3 are left open. Keeping the speed of the induction machine constant, vary the field excitation of the motor from the maximum permissible value down to the one at which the motor drops out of step.

Here again the speed of M_2 will be found to vary, and with it the frequency of the currents supplied by the generator. When the field of M_2 is strengthened, the momentary increase of leading current drawn from the generator raises the induced voltage of the latter with the result that a greater energy component of current is supplied to M_2, thus raising its speed and frequency. This does not go on indefinitely, because the rise in frequency increases the internal impedance drops and tends to lower the terminal voltage. Saturation of course finally limits the voltage which the induction generator may be made to develop by increasing the field current of the synchronous motor.

In carrying out this test, take a series of ten readings, noting generator and motor speeds, volts, amperes, watts and motor field current.

Report. — Calculate the wattless component of the current corresponding to each set of readings, and with these values as abscissæ determine a curve with volts as ordinates, this being the saturation curve of the induction generator. On another curve sheet with motor field ampères as abscissæ construct the curves of motor speed, volts, watts and armature ampères.

Amperes.				Motor Speed.	Generator Speed.	K.W.		Volts.			Wattless Current per Phase.	Remarks.
Motor Field.	1.	2.	3.			1-2.	1-3.	1-2.	1-3.	2-3.		

Experiment 39. — Variation of Generator Speed with Constant Motor Excitation.

(*a*) *Motor Running Free.*

(*b*) *Motor Driving D.C. Generator Connected to a D.C. Source of Power.*

Method. — (*a*) With the connections the same as in the last experiment, switches S_2 and S_3 remaining open, adjust the synchronous motor excitation and generator speed until the rated frequency and voltage are attained. Keep the motor field constant, gradually reduce the generator speed until the motor falls out of step. A decrease in generator speed by lowering the induced voltage causes the motor to receive a momentarily smaller energy current tending to decrease the speed and frequency.

Take six sets of readings of volts, amperes, watts, generator speed and motor speed. The tabulation of the readings should be the same as in Experiment 38.

Report. — (*a*) With generator speed as abscissa plot the curves of volts, amperes, watts and frequency, the four curves being drawn on the same curve sheet. The values of the frequency are to be calculated from the readings of motor speed.

Method. — (*b*) Adjust, as before, the alternating frequency and voltage to their proper values, and by varying the field excitation of M_3 make its voltage exactly equal and opposite to that of the D.C. line. Close switch S_2 and short circuit r_1.

Keeping the field excitations of M_2 and M_3 constant, and varying the speed of the induction generator, it will be found that when this speed is above synchronism the induction machine will drive M_2 as a motor, while below synchronism it will be driven by M_2 as an induction motor.

When due to an increase in speed, a rotary transformer of the induction type passes through synchronism, the slip changes from positive to negative. This is accompanied by a reversal of rotor E.M.F. and current. The stator current, which is always equal to that of the rotor divided by the ratio of transformation, likewise reverses or shifts 180° in phase. This has the effect of reversing the flow of energy so that the machine changes from a motor to a generator, and feeds power into the line.

In the present combination of machines, M_3 must operate at practically constant speed, because it is of small armature resistance, and there is no external resistance between it and the constant potential D.C. power circuit. This means that the frequency of the synchronous machine M_2 is nearly constant. The induction machine therefore will either receive or supply electrical power depending upon whether it is being driven at a speed below or above that corresponding to the frequency of M_2.

Take six sets of readings of all the instruments and of generator and motor speeds, varying the generator speed on each side of synchronism so that the induction generator will develop its full output as a generator when above synchronism, and as a motor when below synchronism.

Amperes.				K.W.		Volts.			Motor Speed.	Generator Speed.	D.C. Machine.		Remarks.
Motor Field.	1.	2.	3.	1-2.	1-3.	1-2.	1-3.	2-3.			Volts.	Amps.	

N. B. — Keep the excitation of M_2 and M_3 constant. Take six sets of readings.

Report. — Tabulate the readings obtained, and explain their relation to the theory of the action of the machines.

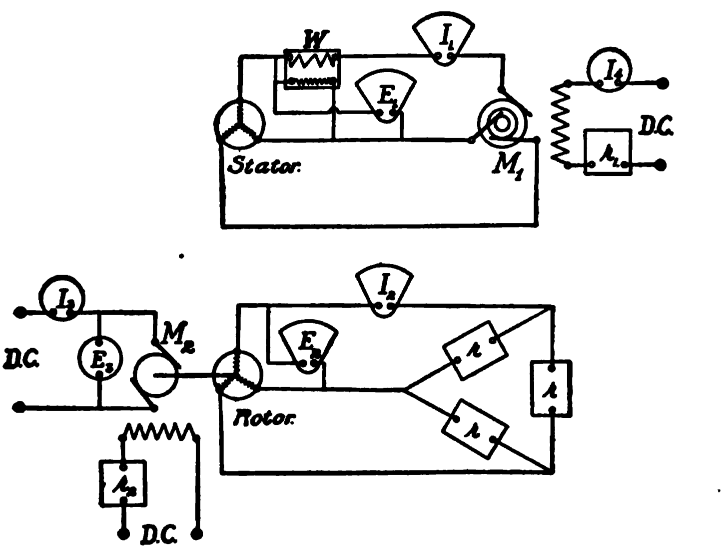
Experiment 40. — The Frequency Changer. Determination of the External Characteristic Curve.

If the rotor of an induction motor, fitted with brushes and collector rings, be driven by a separate source of power, a current of any desired frequency may be drawn from the brushes depending

on the relative speed of the rotor with respect to the stator field. Under all conditions, however, disregarding the magnetizing component of the primary current, the ratio of the currents in stator and rotor is the same, being solely determined by the ratio of turns, without regard to the slip.

Below synchronism the stator supplies energy both to the rotor circuit and to the motor to which the rotor is mechanically connected. Above synchronism the motor supplies energy both to the stator and to the rotor circuit. If the rotor be driven in a direction of rotation opposite to that of the stator field, then the stator will supply energy to the rotor circuit, while the motor will

Fig. 86.



do the same in proportion to its speed and torque. The magnetizing current in the stator is always maintained by the synchronous machine to which the stator is connected.

The frequency of the stator currents must be constant because it is determined by the frequency of M_1. The rotor E.M.F.'s and currents, however, vary in frequency depending upon the relative motion between the rotor conductors and the rotary field which

travels around the stator at a constant angular velocity. Thus, below synchronous speed, the induced frequencies and intensities are greater in proportion to the slip, and very high frequencies may be obtained by driving the rotor against the direction of rotation.

Above synchronism the same thing is true, but as the slip has become negative the E.M.F.'s and currents are altered in phase by 180°.

Method. — Make the connections as shown in Fig. 86. In this diagram the instruments are shown arranged to read volts, ampères and watts in only one phase in both stator and rotor circuits. Polyphase switchboards similar to those shown in Figs. 80 and 81 should here be used in order that the necessary readings may be taken in the other phases. Keep the stator volts and frequency, and the rotor speed constant, and vary the current in the rotor circuit between zero and full load by changing the resistances *r*, *r*, *r*. Note the D.C. motor watts, and the volts, ampères and watts of the stator and rotor circuits. Take three series of readings:

(*a*) Rotor running below synchronism.

(*b*) Rotor running above synchronism.

(*c*) Rotor running in the reverse direction.

N. B. — Keep the stator volts and frequency, and the rotor speed constant.

Rotor							Stator								Synchronous Motor		D.C. Machine		Remarks
Amperes			Volts			Speed	Amperes			Volts			K.W.		Field Amps.	Speed	Amps.	Volts	
1.	2.	3.	1-2	1-3	2-3		1.	2.	3.	1-2	1-3	2-3	1-2	1-3					

Take four sets of readings in each series.

Report. — With rotor current as abscissa plot on the same curve sheet the curves of rotor terminal voltage corresponding to (*a*), (*b*) and (*c*). Tabulate the readings and discuss their relation to the theory of the operation of the frequency changer.

PART III.

Electrical Measurements.

Galvanometers.

There are two types of galvanometer from which most direct current electro-magnetic measuring instruments are derived.

(*a*) The Thomson Galvanometer; suspended magnet and fixed coil.

(*b*) The D'Arsonval Galvanometer; suspended coil and stationary magnet.

The type (*a*) is very sensitive to changes in the surrounding field, so that the zero point is liable to shift. The constant of the instrument is also likely to change on account of an alteration in the strength of the suspended magnetic system. This suspended system must be so adjusted magnetically as to be astatic. Adjustable magnets are mounted on the case in order to control the intensity and direction of the field acting on the suspended needle. For maximum sensitiveness, this directing field should be zero; in other words, the controlling magnet should be so adjusted that its field exactly neutralizes the earth's field acting on the needle. The suspending filament should be a silk or quartz fiber and the degree of sensitiveness attainable varies inversely as the thickness of this filament. Care should be taken to have no torsion in the filament when in the zero position, and the coil should be so placed that its plane is parallel to the earth's field, if greatest sensitiveness is desired.

In general it is not well to make the instrument more sensitive than is absolutely necessary, a delicately adjusted Thomson galvanometer being extremely difficult to work with on account of the influence of vibration and of changing magnetic fields. The sensitiveness can be readily adjusted to suit the work required by

altering the position of the controlling magnets. This is one of the advantages of this type of instrument.

The principal feature of the Thomson galvanometer is the extreme sensitiveness which can be attained. It is not difficult, with a good instrument, to obtain a deflection of one scale division with $\frac{1}{3 \times 10^{10}}$ ampères. The value of the resistance in ohms which, when connected in series with the galvanometer and one volt electromotive force, allows a deflection of one small scale division is called the figure of merit of the instrument.

Type (*b*), the D'Arsonval, is a galvanometer suited to ordinary engineering determinations, where the extreme of accuracy is not necessary, and where an instrument that is easy to work with and not readily injured is indispensable. First in importance, however, is the fact that the strong permanent field of the D'Arsonval galvanometer renders the influence of the surrounding field of small account, and it is for this reason that the D'Arsonval type, more or less modified, has become practically universal in direct-current measuring instruments.

The figure of merit of both types of galvanometer can be altered in various ways:

(1) Changing the length or thickness of the filament.

(2) Changing the strength of the magnets.

(3) Changing the turns of wire in the coil.

The weight of the suspended system affects the period of vibration, but not the figure of merit, or sensitiveness, and the same is true of most kinds of damping. A given current will produce very nearly the same permanent deflection, after the needle has finally come to rest, whether the suspended system is heavy or light, and its motion damped or free. In any galvanometer, deflected but at rest, the influences which balance the turning moment due to the current are merely the torsion of the suspending filament or the attraction of the resultant field; both the inertia and the damping reactions are zero when the velocity is zero, and this is true whether the instrument is deflected or not.

This is a very important principle, as upon it is based the theory of the ballistic galvanometer.

In measuring constant current, or rate of flow of electricity, with a galvanometer, the moving system is deflected from the zero position, and after coming to rest, assumes a new position which is fixed as long as the current continues. The intensity of the current in amperes is measured by means of the angle of deflection. It is frequently desirable to measure, not a current, but an impulse of electricity; for this purpose a ballistic galvanometer, that is, one having a heavy suspended system, is used. When a momentary current of electricity is sent through the coils of the instrument it can be shown that the quantity transmitted is proportional to the sine of half the angle corresponding to the first swing. (See p. 208, eq. 5.)

Galvanometers which are not ballistic, but are intended for the measurement of current, should have the suspended system made as light as possible, so as to come to rest quickly. When a current is flowing, the suspended system after coming to rest deflects through an angle whose tangent is proportional to the ampères. This is true of both Thomson and D'Arsonval types of the instrument, but in the case of the latter, only for small deflections.

Fig. 89.

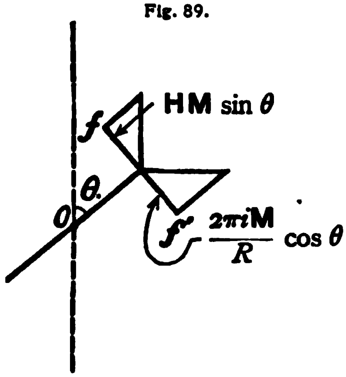


Fig. 89 represents the needle of a Thomson galvanometer pivoted at o. For the sake of simplicity we will assume that the coil has only one turn, and that it has no appreciable thickness.

$\mathbf{M}$ = pole strenght of needle.
R = radius of coil.
$\mathbf{HM}$ = attraction due to earth's field.
$\frac{2\pi i\mathbf{M}}{R}$ = " " " current in coil of one turn.

For equilibrium, the components of these two forces acting in a direction at right angles to the radius R must be equal and opposite.

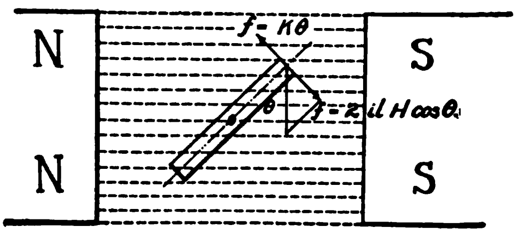
Hence $f = f'$. That is,

$$\mathbf{HM} \sin \theta = \frac{2\pi i \mathbf{M}}{R} \cos \theta = Ki\mathbf{M} \cos \theta, \text{ whence}$$

$$i = \frac{\mathbf{H}}{K} \tan \theta = K' \tan \theta.$$

In the D'Arsonval the two forces at work are the torque due to the current, and the opposing torque due to the torsion of the fiber.

Fig. 90.



In Fig. 90 assume the field $\mathbf{H}$ to be uniform. l = length of coil perpendicular to the plane of the paper.

f = tangential force due to the current = $2il\mathbf{H} \cos \theta$,
f' = " " " " " torsion = $K\theta$.

For equilibrium,

$$f = f', \text{ i. e., } K\theta = 2il\mathbf{H} \cos \theta.$$

Therefore,

$$i = \frac{K}{2lH} \frac{\theta}{\cos \theta} = \frac{K'\theta}{\cos \theta}.$$

For small deflections

$$\theta = \sin \theta,$$

and

$$i = K' \tan \theta,$$

which is the equation of the tangent galvanometer.

This shows that, for small deflections, the D'Arsonval is equivalent to a tangent galvanometer, and it is for this reason that the equations relating to tangent galvanometers apply equally, in practice, to both the Thomson and D'Arsonval types.

In addition to measuring current, a galvanometer may also be used to measure quantity of electricity, when the suspended system is heavy enough. Such an instrument as already explained, is called a ballistic galvanometer, from the Greek verb βάλλω, to throw, on account of the manner in which it is used. It can be shown to be a property of this form of galvanometer, that, when a momentary current of electricity is sent through it, the quantity is proportional to the first throw of the needle, the only necessary condition being that the current must be of such short duration that it shall have ceased by the time the needle starts to move appreciably.

The advantage of being able to measure an impulse produced by a momentary current of electricity lies not so much in the importance of the impulse itself as in that of the cause that produces it; thus the capacity of a condenser can be found by charging it with a known voltage and measuring the quantity of the charge by discharging the condenser through a ballistic galvanometer. In a similar way this form of galvanometer can be used for the purpose of measuring lines of magnetic force.

Let it be required to measure the number of lines of force ϕ enclosed by a coil of wire. Connect the coil to a ballistic galvanometer and remove the coil from the field very quickly; a momentary current of electricity will be produced in the galvanometer, and if the suspended system has enough inertia, it will not start to move appreciably until after this momentary current has fallen to zero.

The value of the current at any instant during the impulse will be

$$i = \frac{dQ}{dt} = \frac{n\frac{d\phi}{dt} - L\frac{di}{dt}}{R}, \tag{1}$$

where n is the number of turns in the coil.

From this expression the total quantity which has passed through the coil during the impulse, may be calculated by integrating equation (1) throughout the interval of time, t_0, occupied by the passage of the current. This quantity is

$$Q = \int_0^{t_0} i\,dt = \frac{1}{R}\left[n\int_0^{t_0} d\phi - \mathsf{L}\int_0^{t_0} di\right],$$

$$Q = \frac{n\phi}{R}. \qquad (2)$$

As already stated it can be shown that the quantity of electricity Q is proportional to the first throw of the needle after the impulse; it is evident, therefore, that if this is the case ϕ may be calculated from equation (2), Q being determined from its relation to the observed deflection. (See equation 16, page 212.)

It is necessary, before proceeding further, to explain how it is that the quantity Q which passes through the coil during the impulse may be expressed in terms of the first throw of the needle. The expression resulting from this proof is the same for both D'Arsonval and Thomson ballistic galvanometers. The value of Q will, therefore, be deduced for a Thomson instrument.

Let I = moment of inertia of suspended magnet.
M = magnetic moment of suspended magnet.
K = constant of galvanometer.
H = strength of the field.
i = current in C.G.S. units.

Let a momentary current be sent through the instrument, the duration being so short that the needle does not begin to move appreciably until the current has ceased.

During the impulse, the equation of moments will be

$$\frac{\mathsf{I}d^2\theta}{dt^2} = \mathsf{M}Ki\cos\theta;$$

but since the needle has not begun to deflect appreciably, θ is zero, and the equation becomes

$$\frac{d^2\theta}{dt^2} = \mathsf{M}Ki. \qquad (3)$$

In these equations the moment due to damping is neglected as, at the initial instant, it is small compared to the inertia reaction.

Let the interval of time occupied by the impulse be

$$\Delta t = t_2 - t_1,$$

t_2 being the time when the impulse ceases, and the suspended system begins to move with an initial velocity

$$\left(\frac{d\theta}{dt}\right)_0.$$

Integrating equation (3) throughout this time interval,

$$\mathsf{I}\int_{t_1}^{t_0} \frac{d^2\theta}{dt^2}\,dt = \mathsf{M}K\int_{t_1}^{t_2} i\,dt,$$

and

$$\mathsf{I}\left(\frac{d\theta}{dt}\right)_0 = \mathsf{M}KQ.$$

Solving for Q, we have

$$Q = \frac{\mathsf{I}}{\mathsf{M}K}\left(\frac{d\theta}{dt}\right)_0. \tag{4}$$

In order to render equation (4) of any practical value, it is necessary to transform it, so as to express the right hand member in terms of quantities which can be easily determined experimentally.

Let us consider the motion of the needle after the impulse has ceased. The needle then oscillates to and fro under the influence of the earth's field, the torsion of the fiber and the frictional or other resistances which damp the oscillations. The equations of motion will be the same as for a pendulum. In other words we have here a case of simple harmonic vibration.

The energy imparted to the moving system by the impulse is evidently

$$W = \tfrac{1}{2}\mathsf{I}\left(\frac{d\theta}{dt}\right)_0^2.$$

If we neglect the retarding moments due to torsion and damping, the energy W will then be all used up in moving the needle

against the moment $\mathbf{HM} \sin \theta$ due to the earth's field. At the end of the first throw, therefore,

$$\tfrac{1}{2}\left(\frac{d\theta}{dt}\right)_0^2 \mathbf{I} = \int_0^{\theta_1} \mathbf{MH} \sin \theta d\theta,$$

$$\therefore \left(\frac{d\theta}{dt}\right)_0 = \sqrt{\frac{2\mathbf{MH}}{\mathbf{I}}(1 - \cos \theta_1)} = 2\sqrt{\frac{\mathbf{MH}}{\mathbf{I}}} \sin \tfrac{1}{2}\theta_1.$$

Substituting this value in equation (4)

$$Q = 2\frac{\mathbf{H}}{K}\sqrt{\frac{\mathbf{I}}{\mathbf{MH}}} \sin \tfrac{1}{2}\theta_1.$$

It will be shown later that the time of vibration without damping is

$$T = 2\pi\sqrt{\frac{\mathbf{I}}{\mathbf{MH}}}.$$

Substituting this value in the above equation we have

$$Q = \frac{\mathbf{H}T}{\pi K} \sin \tfrac{1}{2}\theta_1. \tag{5}$$

In this equation damping is neglected, and it is necessary to find the relation between the actual angle θ_1' observed in practice, and the theoretical angle θ_1, which is the theoretical deflection which would occur if there were no damping. Similarly the theoretical time T, can be expressed in terms of the actual time of vibration, T', in the calculation of which damping is taken into account.

In order to calculate T and θ, let us again consider the motion of the needle after the impulse has ceased and the needle is swinging freely after the manner of a pendulum. The motion of the needle is then the result of the combined effect of the moments due to inertia, the earth's field, damping and torsion. At any instant, while the needle is swinging, the sum of these moments is equal to zero or

$$\mathbf{I}\frac{d^2\theta}{dt^2} + \mathbf{MH} \sin \theta + a\frac{d\theta}{dt} + b\theta = 0. \tag{6}$$

In a properly adjusted instrument, the moment of torsion may be neglected, leaving only the moments $\mathbf{MH} \sin \theta$, due to the earth's field, and $a \frac{d\theta}{dt}$, that due to damping, in addition to the moment due to inertia, $\mathsf{I} \frac{d^2\theta}{dt^2}$.

It will be observed that the moment due to damping, $a \frac{d\theta}{dt}$, is taken as being proportional to the first power of the velocity. In most cases this is not strictly true, and it is therefore necessary in a good instrument that the damping reaction should be very slight. Eddy currents are perhaps the only form of damping in which the retarding effect is theoretically proportional to the first power of the velocity, and in instruments damped by the motion of a conductor in a magnetic field the damping reaction may be therefore extremely pronounced without affecting the use of the instrument as a ballistic galvanometer. A Weston millivoltmeter, in which the damping is due to eddy currents, makes an excellent substitute for a ballistic galvanometer on this account.

In this discussion it will be assumed throughout that the deflections are very small angles. In equation (6), therefore, θ may may be written for sin θ.

Making this change,

$$\mathsf{I}\frac{d^2\theta}{dt^2} + \mathbf{MH}\theta + a\frac{d\theta}{dt} = 0. \tag{7}$$

The solution of a differential equation of this form is $\theta = e^{mt}$.
Substituting and solving for m we have

$$m = -\frac{a}{2\mathsf{I}} \pm \sqrt{\frac{a^2}{4\mathsf{I}^2} - \frac{\mathbf{HM}}{\mathsf{I}}}.$$

This gives two values m_1 and m_2, therefore the value of θ given by the expression

$$\theta = Ae^{\frac{-at}{2\mathsf{I}}}\left(e^{t\sqrt{\frac{a^2}{4\mathsf{I}^2} - \frac{\mathbf{HM}}{\mathsf{I}}}} - e^{-t\sqrt{\frac{a^2}{4\mathsf{I}^2} - \frac{\mathbf{HM}}{\mathsf{I}}}}\right)$$

will also satisfy equation (7).

Now

$$2j \sin x = e^{jx} - e^{-jx},$$

therefore,

$$\theta = e^{-\frac{at}{2I}} \times 2Aj \sin t\sqrt{\frac{HM}{I} - \frac{a^2}{4I^2}}. \tag{8}$$

In equation (8) $t = 0$ when $\theta = 0$; the needle is then in its zero position. Counting the time t from this instant, T' seconds will elapse while the needle swings first to one side and then to the other and back again to the initial zero position. At this instance $t = T'$, and since the needle has vibrated through a complete period, the angle θ is again zero, and

$$t\sqrt{\frac{HM}{I} - \frac{a^2}{4I^2}} = 2\pi.$$

It follows from this that

$$T' = \frac{2\pi}{\sqrt{\frac{HM}{I} - \frac{a^2}{4I^2}}}. \tag{9}$$

The only difference between T in equation (5) and T' lies in the fact that the former is the time of vibration with no damping, or a equal to zero. Imposing this condition in equation (9) we see that as already stated

$$T = \frac{2\pi}{\sqrt{\frac{HM}{I}}}. \tag{10}$$

By means of equations (8) and (9) we obtain

$$\theta = 2Aje^{-\frac{a}{2I}t} \sin\frac{2\pi}{T'}t. \tag{11}$$

The first swing of the needle is

$$\theta_1' = 2Aje^{-\frac{a}{2I}\frac{T'}{4}}; \tag{12}$$

because at the end of the first swing $t = T'/4$.

In the same way the successive elongations of the needle are

$$\theta_2' = 2Aje^{-\frac{a}{2l}\frac{3T'}{4}};\ \theta_3' = 2Aje^{-\frac{a}{2l}\frac{5T'}{4}}, \text{ etc.}$$

THE LOGARITHMIC DECREMENT.

From the above it is plain that the ratio of successive swings is constant. Thus

$$\frac{\theta_{n-l}}{\theta_n} = e^{\frac{aT'}{4l}}.$$

and

$$\log_e \frac{\theta_{n-l}}{\theta_n} = \frac{aT'}{4l} = \lambda. \tag{13}$$

The quantity λ is known as the logarithmic decrement. Since it is the logarithm of the ratio of successive deflections it is quite easy to determine it experimentally by simply setting the needle in oscillation and noting the turning points of a series of swings; also it is found that the relations between T and T', and between θ_1 and θ_1' can be conveniently expressed in terms of λ. Thus from equations (9), (10) and (13), we may obtain

$$T = \frac{T'\sqrt{\frac{HM}{l} - \frac{a^2}{4l^2}}}{\sqrt{\frac{MH}{l}}} = \frac{T'\sqrt{\frac{4\pi^2}{T^2} - \frac{4\lambda^2}{T'^2}}}{\frac{2\pi}{T}}.$$

Since λ is a very small quantity and T does not differ much from T', we may write

$$\frac{4\lambda^2}{T'^2} = \frac{4\lambda^2}{T^2}.$$

The value of T is then given by the equation

$$T = \frac{T'\sqrt{\pi^2 - \lambda^2}}{\pi}. \tag{14}$$

By making a equal to zero in equation (12) the value of θ is found to be

$$\theta_1 = 2Ai,$$

therefore,

$$\frac{\theta}{1} = \frac{\theta_1'}{e^{-\frac{\lambda}{2}}}.$$

By McLaurin's theorem, neglecting small terms, the value becomes

$$\theta_1 = \theta_1' \frac{1}{\left(1 - \frac{\lambda}{2}\right)} = \theta_1'\left(1 + \frac{\lambda}{2}\right), \tag{15}$$

We may now substitute in equation (5) the values of θ and T given by equations (14) and (15) and obtain

$$Q = \frac{\mathsf{H}T'\sqrt{\pi^2 - \lambda^2}}{\pi^2 K} \sin \tfrac{1}{2}\left[\theta_1'\left(1 + \frac{\lambda}{2}\right)\right].$$

Now λ is usually a very small quantity, and may be neglected in comparison with π^2. Also, for small swings,

$$\sin \tfrac{1}{2}\left[\theta_1'\left(1 + \frac{\lambda}{2}\right)\right] = \left(1 + \frac{\lambda}{2}\right) \sin \tfrac{1}{2}\, \theta_1',$$

and

$$\sin \tfrac{1}{2}\theta_1' = \tfrac{1}{2}\theta_1'.$$

The value of Q, therefore, is

$$Q = \frac{\mathsf{H}T'}{\pi K}\left(1 + \frac{\lambda}{2}\right)\tfrac{1}{2}\theta_1'.$$

Let S_1 be the scale reading corresponding to θ_1'. Then since this angle is small, L being the distance from the mirror to the scale, we finally obtain

$$Q = \frac{\mathsf{H}T'}{2\pi K}\left(1 + \frac{\lambda}{2}\right)\frac{S_1}{L}. \tag{16}$$

Experimental Determination of λ and T'. — Cause the galvanometer needle to swing back and forth, and note the time of one complete oscillation. This may be done by measuring the time for n complete swings and dividing it by n. In this way T' may be determined to any desired degree of accuracy. λ may be simi-

larly determined by noting the number of scale divisions traversed in the first and in the nth swings. Then

$$\lambda = \frac{1}{n-1} \log_e \frac{S_1}{S_n} = 2.30 \log 10 \frac{S_1}{S_n}.$$

In this equation S_1 and S_n denote the entire arcs traversed in each case between two successive turning points.

As an example, suppose that, as the needle swings, the readings of the turning points are $49 - 32$, $48 - 33$, $47 - 34$; then

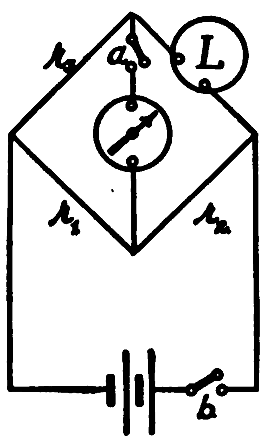
$$\lambda = \tfrac{1}{2} \log_e \frac{49-32}{47-34}.$$

In determining λ and T' the swings should have about the same magnitude as the deflections read in the measurement for which the galvanometer is being used.

Experiment 1. — Measurement of an Inductance.

The coil of which the inductance is to be measured is connected, as shown in Fig. 91, in one branch of a Wheatstone bridge, which is then balanced for resistance in the usual way. (See Experiment 8.) Let i_1 denote the continuous current then flowing in the branch of the bridge which contains the variable resistance r_3. If the battery key is now opened with the galvanometer key still closed, there will be an electromotive force set up in the branch containing the self-induction proportional to the rate of change of the current. This will momentarily upset the equilibrium of the bridge, and the galvanometer will therefore receive an impulse for some short interval of time, $t_2 - t_1$. The total quantity of electricity passing through the galvanometer will be

Fig. 91.



$$Q = \int_{t_1}^{t_2} x dt,$$

where x is the current through the galvanometer at any instant. The current x is, however, evidently proportional to the E.M.F. of self induction which produces it. Therefore

$$x = K_1 \mathsf{L} \frac{di}{dt},$$

and

$$Q = K_1 \mathsf{L} \int_{t_1}^{t_2} \frac{di}{dt}\, dt = K_1 \mathsf{L} i_1.$$

From the theory of the ballistic galvanometer, equation (16), we may write

$$K_1 \mathsf{L} i_1 = \frac{1}{2} \frac{\mathsf{H} T'}{\pi K}\left(1 + \frac{\lambda}{2}\right)\frac{S_1}{L},$$

whence

$$\mathsf{L} = \frac{1}{2} \frac{\mathsf{H} T'}{\pi K K_1 i_1}\left(1 + \frac{\lambda}{2}\right)\frac{S_1}{L}.$$

The quantity $\frac{\mathsf{H}}{K K_1 i_1}$ would be difficult to determine experimentally. It is therefore, eliminated by the following method:

Close the battery key. Since the bridge is balanced for resistance, no current will then flow through the galvanometer upon closing the galvanometer key. Keep this key closed, and change the variable resistance by a very small amount ΔR. The bridge will now be slightly unbalanced, and a constant current x' will flow through the galvanometer, producing a permanent deflection, θ, such that

$$x' = \frac{\mathsf{H}}{K} \tan \theta = \frac{\mathsf{H} S}{K L}.$$

S is the value of the permanent deflection in scale divisions, and L the distance between mirror and scale. The current i_1 will be substantially unchanged, and $i_1\ \Delta R$ will be the E.M.F. producing the current in the galvanometer, and to this E.M.F. the current x' must be proportional. Therefore

$$x' = K_1 i_1 \Delta R = \frac{\mathsf{H} S}{KL} \text{ and } \frac{\mathsf{H}}{KK_1 i_1} = \frac{\Delta RL}{S}.$$

Substituting this value in the equation for L we have

$$\mathsf{L} = T' \frac{\Delta R}{2\pi}\left(1 + \frac{\lambda}{2}\right)\frac{S_1}{S}.$$

Method. — First balance the bridge for resistance, choosing the resistance of the ratio arms, r_1 and r_2, so that all four arms of the bridge shall be approximately of the same resistance. In order to obtain a very accurate balance, part of arm r_3 may consist of slide wire resistance.

With the bridge thus balanced, and the galvanometer at rest, open the battery key, keeping the galvanometer key closed.

Having noted the first swing S_1, close the galvanometer key, and bring the instrument to rest; then, since nothing has been done to unbalance the bridge, there will be no deflection and the instrument will once more read zero.

Change the resistance of the variable branch, r_3, by some known small amount ΔR, and as soon as the galvanometer has stopped swinging note the permanent deflection S.

λ and T' may now be determined, as described on pages 212 to 213.

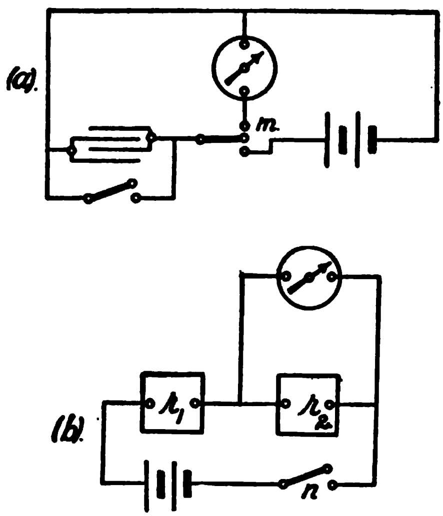
If a D'Arsonval galvanometer is used, λ and T' should be determined with the bridge balanced and the galvanometer key closed in order that the conditions may be the same as when S_1 was determined.

This is because the bridge forms a more or less complete short circuit, through which the moving coil sends a current every time it moves through the field. The moving coil then acts as a generator, and its motion is thereby damped, thus making the time of vibration a function of the bridge resistances, while the value of λ is at the same time greatly increased.

Experiment 2. — Measurement of the Capacity of a Condenser. The necessary apparatus for the first portion of the determination consists of a ballistic galvanometer, the condenser, a constant battery and a double throw key, *m*.

Arrange the connections so that when the key is closed in one direction the battery charges the condenser, while the other position of the key causes the condenser to discharge through the galvanometer. There should also be an arrangement for short circuiting the condenser after each discharge, so as to remove any residual charge. See Fig. 92 (*a*).

Fig. 92.



In being charged by a battery whose voltage is E, the condenser receives a charge $Q = CE$, the capacity being denoted by C.

When the condenser is then discharged through the galvanometer the entire charge of the condenser passes through the coils. The resistance of the galvanometer circuit makes no difference except that it increases the length of time during which the impulse lasts and may on this account cause an error in the

result. The first throw of the needle due to the discharge is related to the quantity Q by the equation

$$Q = CE = \tfrac{1}{2}\frac{\mathbf{H}T'}{\pi K}\left(1 + \frac{\lambda}{2}\right)\frac{S_1'}{L}.$$

(See equation (16).)
Therefore

$$C = \tfrac{1}{2}\frac{\mathbf{H}T'}{\pi KE}\left(1 - \frac{\lambda}{2}\right)\frac{S_1'}{L}.$$

In order to eliminate the quantity $\left(\frac{\mathbf{H}}{KE}\right)$ which would be difficult to measure in any other way, the following operation is performed:

Connect the galvanometer directly in series with the battery through a high resistance, and let R denote the sum of the values of this resistance and of the galvanometer resistance. Close the key n, and when the galvanometer has come to rest note the permanent deflection S. Then,

$$\frac{E}{R} = \frac{\mathbf{H}}{K}\tan\theta = \frac{\mathbf{H}S}{KL},$$

R denoting the entire resistance of the circuit. Therefore

$$\frac{\mathbf{H}}{KE} = \frac{L}{RS}.$$

Substitute this value in the equation for C, and we have

$$C = \tfrac{1}{2}\frac{T'}{\pi R}\left(1 + \frac{\lambda}{2}\right)\frac{S_1}{S}.$$

It is sometimes convenient in the second part of the experiment to obtain a known fraction of E by taking the drop across a known fraction of a high resistance $r_1 + r_2$ connected across the battery as in Fig. 92 (b). By this means, since the working voltage is very small it is not necessary to use a resistance in series with the galvanometer, while if this device were not resorted

to a resistance of several megohms might be needed. Thus if the voltage employed is some fraction yE of the battery voltage,

$$\frac{yE}{R_g} = \frac{\mathsf{H}}{K} \tan \theta,$$

where R_g is the galvanometer resistance, and the quantity y is obtained from the equation

$$y = \frac{r_2 R}{r_1(r_2 + R_g) + r_2 R_g}.$$

In this case substitute $\frac{R_g}{y}$ for R in the equation for C, as given above.

Almost all dielectrics, with the exception of mica, exhibit the phenomenon of absorption, so that usually the time of charging must be taken into account. In telephone practice it is customary to allow a sufficient time to elapse so that a further increase in the time of charging no longer produces an increased throw on discharge.

Another characteristic of condensers is that, when left charged with the charging voltage removed, leakage currents occur by convection and conduction, which gradually discharge the plates.

In testing a condenser with the ballistic galvanometer both these points should be considered.

Method. — Determine the capacity of the condenser for successively greater increments in the time of charging. For a three M.F.D. condenser readings may be taken at 1, 3, 6, 12, and 24 seconds.

Determine the capacity of the condenser, after charging for five seconds in each case, leaving the key m in the middle, insulating, position for successively greater numbers of seconds. The same time values may be taken in this series of curves as in the other.

In taking a capacity reading, first charge the condenser, and at the same time bring the galvanometer to rest. Then reverse the key m, so as to discharge the condenser through the gal-

vanometer, noting the first throw S_1 of the needle. Next connect the galvanometer in series with a fraction of the battery voltage as described. Close the key *n*, and when the galvanometer has come to rest, note the steady deflection S.

The time of vibration and the logarithmic decrement should be determined in the manner already explained.

Be careful to short circuit the condenser after each discharge in order to neutralize any residual polarization.

Report. — Plot two curves on the same sheet corresponding to the two series of readings, making microfarads the ordinates and time the abscissa in each case.

Experiment 3.—Determination of the Leakage Coefficient of a Machine.

The leakage coefficient α of a machine is the ratio obtained by dividing the flux in the field by that in the armature,

$$\alpha = \frac{\phi}{\phi_a}.$$

The value of α depends to a certain extent on the permeability of the different portions of the magnetic circuit, and therefore on the field current. The magnetic leakage is also affected by the current in the armature when the machine is in operation.

In order to determine α, a few turns of wire are wound around a field spool and connected to a ballistic galvanometer. As long as the field current remains constant there will be no motion of the galvanometer, but on breaking the field circuit the lines of induction in the field vanish, cutting the test coil, thereby producing a deflection, S, which is proportional to the total field flux ϕ. [See equations (2) and (16).]

The galvanometer is now connected to a similar test coil of the same number of turns wound around the armature in such a way as to enclose the total armature flux ϕ_a. Adjust the field current to the same value as before, and when the galvanometer has been brought to rest, again throw the field switch. The resulting deflection, S_a, will be similarly proportional to ϕ_a. Therefore the

leakage coefficient may be directly calculated from the equation

$$\alpha = \frac{S}{S_a}.$$

If the machine has a high leakage coefficient it may be interesting to determine where most of the leakage occurs. This may be done by means of a small exploring coil connected to the galvanometer. By placing this coil in various positions about the machine and breaking the field current, deflections may be obtained showing the relative values of the stray field in the different portions of the structure.

Method. — Determine α as described, for ten different values of the field current.

Using the ballistic galvanometer connected to the exploring coil determine the relative values of the stray field at six points about the machine where leakage might be expected to occur. On throwing the field switch the deflection of the galvanometer will be a measure in each case of the lines of force enclosed by the coil, and consequently the deflections obtained with the coil in different positions will give an accurate idea of the leakage field. The normal field current should be used throughout this part of the experiment.

Readings should always be taken on breaking the field current, that being the only way in which definite results can be obtained; this is because the magnetism rises very slowly on closing the field switch, while on breaking the circuit the field disappears with comparative rapidity.

It should be remembered that the period of the galvanometer must be so great that it will not move appreciably before the impulse of the current due to the dying out of the field has ceased. In testing large machines it is necessary on this account to increase the inertia of the movable system of the galvanometer by the addition of weights. The proper period of vibration may have to be, in certain cases, considerably longer than a minute.

Report. — Tabulate the readings and the calculated values of α. Construct a curve having the value of α as ordinates and those of the field current as abscissæ.

Draw a diagram of the machine, showing by numbers the various positions of the exploring coil. These numbers should refer to the corresponding deflections in the tabulation of the readings.

Experiment 4. — Determination of Permeability.

(*a*) *Hopkinson Method.* — The apparatus shown in Fig. 93 consists of a rectangular soft iron yoke, y, the cross-section of which is so large compared with that of the specimen SS that its magnetic reluctance may be neglected. The specimen to be tested is in two parts. These are inserted in the magnetizing coils, qq, and the ends are made to touch through a small movable test coil, C_1, mounted on a spring. This test coil is connected to a ballistic galvanometer.

The specimens should be demagnetized before beginning the experiment. The easiest way to do this is to place it in an alternating magnetic field. The same result may, however, be accomplished with continuous current by magnetizing the specimen in the opposite direction to that in which it is found to be magnetized, the M.M.F. being so adjusted that when it is removed the specimen will show zero induction.

The object of the test is to determine a curve between permeability and induction. The values of μ are calculated by means of the equation $\mu = \frac{\mathbf{B}}{\mathbf{H}}$ by determining the coincident values of $\mathbf{B}$ and $\mathbf{H}$. In order to obtain the necessary data for the permeability curve it will therefore be necessary to increase $\mathbf{H}$ by successive steps up to some maximum value, and to determine for each reading of $\mathbf{H}$ the corresponding value of $\mathbf{B}$.

Insert the specimen in its position, so that the opposite ends meet through the test coil C_1. With switch d_2 open, close d_1 and pass a current i_1, through the magnetizing turns, the total

number of lines of induction in the specimen is then given by the equation

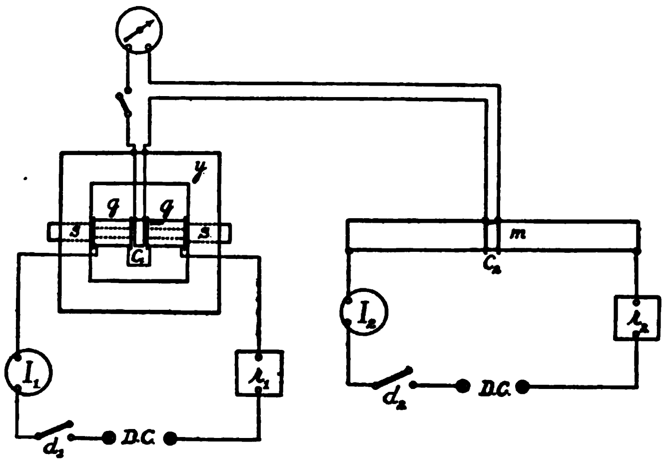
$$\phi = \frac{\frac{4\pi n i_1}{l}}{\frac{l}{A\mu}} = \mathrm{H}A\mu. \tag{17}$$

In this expression

$n =$ number of turns in magnetizing coils.

$l =$ length of specimen in cm.

Fig. 93.



$A =$ cross-section of specimen in sq. cm.

The dimensions l and A refer to the part of the specimen which is turned down so as to offer a reluctance greater than the rest of the magnetic circuit. As appears in the equation for ϕ, all other reluctances than that of the length l of the specimens are neglected. This is liable to be a grave source of error in the determination of the values of μ.

If one half of the specimen is quickly withdrawn from the yoke while current is flowing through the magnetizing coils, the test coils will spring out and cut the lines ϕ. This will give the galvanometer an impulse, and the first swing S_1 will be proportional to the quantity of electricity Q passing through the galvanometer. See equation (16).

From equation (2) however, we see that Q is likewise proportional to the number of lines of force cut by the test coil. We have, therefore,

$$\phi = KS_1.$$

Combining this equation with equation (17), and remembering that

$$\frac{\phi}{A} = \mathbf{B}.$$

We have

$$\mathbf{B} = \frac{KS_1}{A} = \frac{4\pi ni}{\frac{l}{\mu}} = \mu\mathbf{H}, \tag{18}$$

where n is the total number of turns in the magnetizing coils, and K is the galvanometer constant.

The constant K in equation (18) is the number of lines of force cutting the test coil which will produce a deflection of 1 scale division. The determination of K must always be made whenever the ballistic galvanometer is used to measure a number of lines of induction. What follows therefore applies to part (*b*) of this experiment, and also to experiment (5).

Determination of the galvanometer constant.

In this determination a very long solenoid m is used which is wound on a wooden core. At the middle of this solenoid is wound a calibrating coil, which is connected with the galvanometer. Open switch d_1 and close d_2. If a current i' is then passed through the magnetizing turns, it will produce a flux ϕ', at the middle section of the solenoid such that

$$\frac{\phi'}{A'} = \frac{4\pi n' i'}{l'}. \tag{19}$$

In this equation $n' A'$ and l' are respectively the number of magnetizing turns, the cross-section and the length of the solenoid.

On suddenly breaking the magnetizing circuit, the lines of force ϕ' fly out and cut the turns of the calibrating coil c_2, producing a throw of the galvanometer such that

$$\phi' = K'S'. \tag{20}$$

If the number of turns, t and t', of the test coil C_1 and of the calibrating coil C_2 are the same, it is evident that K will be equal to K' while if t' is greater than t, K' will be proportionately less than K. Therefore,

$$\frac{K}{K'} = \frac{t'}{t}. \tag{21}$$

By equations (19), (20), and (21) we have, therefore,

$$K = \frac{t'\dfrac{\phi'}{S'}}{t} = \frac{4\pi n' i' t' A'}{S' l' t}. \tag{22}$$

The test coil and calibrating coil are connected permanently in series with each other and with the galvanometer. This is necessary in order not to change the resistance across the galvanometer, on which, in the case of a D'Arsonval, the damping and consequently the period of vibration partly depend.

Method.—Demagnetize the specimen. Then bring the galvanometer to rest, close d_1, and with d_2 open, pass a small current through the magnetizing turns. Close the galvanometer key, pull out one half of the specimen and note the throw obtained. Repeat this operation for about ten successively greater values of **H** between zero and the maximum. It is best to adjust the current before inserting the specimen. By this means the points obtained will always correspond to the true permeability curve, and adjusting the current cannot introduce errors due to hysteresis.

Determine K by means of the long solenoid. Pass a sufficient current through its magnetizing turns to produce a convenient throw of the galvanometer coil on breaking the circuit. Note this throw, and calculate K from a number of similar readings by means of equation (22).

Great care should be taken in every case to bring the galvanometer completely to rest before taking a reading. It is also especially important that the period of the galvanometer should

be long enough so that the coil does not start to move appreciably until the impulse has ceased.

Report. — Tabulate the readings of current and the corresponding deflections obtained in both parts of the determination. Calculate K, $\mathbf{H}$, and μ. Plot two curves on the same sheet; (1) with $\mathbf{B}$ as ordinate and $\mathbf{H}$ as abscissa; (2) with μ as ordinate and $\mathbf{B}$ as abscissa.

(*b*) *Ewing Magnetic Bridge.* — In the Ewing double bridge method of measuring permeability which will now be described the error involved by the use of a magnetic yoke is corrected, and the method is consequently an excellent one for standardizing samples.

The specimen is turned down to a diameter of about $\frac{3}{8}''$ and sawed through in the middle so as to make two rods each 12.56 or 4π cm. in length. These are placed parallel to each other, and the ends connected by two yokes which may be moved along the bars, so as to increase or diminish the length L_1 of the iron between the yokes.

A test coil and a pair of magnetizing coils are wound around the specimens between the yokes, much as in the Hopkinson method, and the test coil is connected to a ballistic galvanometer the deflection of which is a measure of the magnetic flux.

In working by this method it is necessary to reverse the M.M.F., thus obtaining deflections due to twice the flux corresponding to it; merely opening the magnetizing circuit would not reduce the flux to zero, on account of residual magnetism.

If n is the number of effective magnetizing turns the total M.M.F. will be

$$.4\pi n_1 i = \mathbf{H} L_1 + E, \tag{23}$$

where E is a correction depending on the reluctances of the yokes and joints. The apparent value of $\mathbf{H}$ corresponding to any value of $\mathbf{B}$ when determined experimentally will be

$$\mathbf{H}' = \frac{.4\pi n_1 i}{L_1}.$$

Let $L_1 = 12.56$ cm., $n_1 = 100$, since this simplifies calculation, and determine a curve between **B** and **H'**.

Having done this slide the yokes nearer together and diminish the number of magnetizing turns so that

$$L_2 = 6.28 = \frac{L_1}{2}, \text{ and } n_2 = 50 = \frac{n_1}{2}.$$

The true value of **H** will be given by the equation

$$\mathbf{H} = \frac{.4\pi n_2 i_2}{L_2} - \frac{E}{L_2}, \tag{24}$$

and the apparent magnetic force will be

$$\mathbf{H}'' = \frac{.4\pi n_2 i}{L_2}.$$

As before, determine a curve between **B** and **H''**, plotting both this and the previous curve on the same sheet of cross-section paper. For any one value of **B** in the specimens, the true **H** must be the same, hence by means of equations (23) and (24) we may write

$$\frac{E}{L_1} = \mathbf{H}'' - \mathbf{H}'.$$

The true relation between **B** and **H** may therefore be calculated from the experimental results or determined graphically from the curves already plotted by subtracting $\frac{E}{L_1}$ from each succeeding value of **H'**. $\frac{E}{L_1}$ is not a constant, but varies with the magnetic density.

In using the double bridge the method of reversals should be employed. In this method the magnetizing current is reversed by means of a snap switch, so that the flux cutting the test coil is always twice that corresponding to the magnetizing current.

Method. — Insert the specimens in one set of magnetizing coils, clamping the yokes firmly so as to make magnetic leakage

a minimum. Adjust the magnetizing current to its maximum value, throw the reversing switch and note the galvanometer deflection. Repeat this process for successively smaller values of **H** until a sufficient number of readings have been taken to allow an accurate curve to be constructed from them.

Another similar set of readings must then be taken using the other pair of coils, a corresponding change being made in the distance between the yokes.

It will be found that the results will be more accurate if the iron is put through two or three magnetic cycles before taking a reading, this being done by throwing the reversing switch first in one direction and then in the other several times with the galvanometer short circuited. K must be determined as described in part (a) of this experiment. It should be determined, however, by "reversals."

Report. — Plot two curves with **B** as ordinate and **H** as abscissa, on the same sheet of cross-section paper. From these determine the corrected curve as described, and plot it with them. Also on the same sheet plot the calculated values of μ obtained from the corrected **BH** curve, with respect to **B** as abscissa.

The double bridge method just described is generally used for the standardization of a specimen. The method is modified in the following way when it is desired to compare unknown samples with the specimen already standardized.

A bridge is employed similar in construction to that already described, but containing the standard in one coil and the sample in the other. The yokes are fixed in position and are fitted with iron projections so as to form pole pieces between which is pivoted a small magnetic needle. The currents in the two coils are separately controllable, and in making a determination they are adjusted so that the needle does not deflect from its zero position. It is evident that under these circumstances the flux is the same in both halves of the magnetic circuit formed by the standard and the sample, and their relative permeability is given by the

relation of the currents in the two coils. The true permeability of the sample may be found by reference to the known permeability curve of the standard.

The methods given above are applicable to the determination of permeability in bars or rods of iron which may be samples of material to be used in the construction of D.C. magnets, usually the cores and yokes of direct current machines. The same general ideas, however, may be applied to the testing of laminations for A.C. work.

One of the best means for dealing with laminations is to construct from them a small rectangular core consisting of about a half dozen thicknesses, piling up the sheets in the manner well known in transformed construction so that the joints overlap. A core of this kind may be treated without appreciable error as if it were a closed magnetic circuit. The method, (*b*), may therefore be applied to it without the necessity of eliminating any constant reluctance due to a yoke.

Method. — Determine the constant of the galvanometer as described in method (*a*); but this should be done here by reversing the current and not by simply breaking it; otherwise, a factor of 2 will be introduced in working out the results.

In carrying out the test, begin with the largest magnetizing force, reverse the current and note the deflection of the galvanometer. Repeat this operation with ten successively smaller values of the current.

It will be found that in order to secure the best results, at each value of the current, the iron should be put through several magnetic reversals by operating the reversing switch before the actual reading is taken. During this preliminary reversing of the current the galvanometer should be short circuited in order to keep it from swinging.

The curves already described are determined by this method.

Experiment 5. — Determination of the Hysteresis Loop in a Uniformly Wound Iron Ring with Closed Magnetic Circuit and Uniform Cross-section.

(*a*) *Method of Opposed Magnetizing Coils.* — A test coil is wound on the core and connected to a ballistic galvanometer. The number of turns must be such that the maximum flux variation which is to take place in the core will produce a deflection of at least 100 small scale divisions, in order that the scale may be read with accuracy.

Two magnetizing windings, each of n turns, must also be put on the core; the turns of circuit No. 1 being wound directly over those of circuit No. 2, both being wound uniformly over the entire circumference.

Before beginning the determination the core should be demagnetized, if possible with an alternating current, by putting the magnetism of the core through a succession of magnetic cycles of gradually decreasing amplitude.

Let a constant current i_1 be passed through circuit No. 1 of such value as to produce the maximum value of the induction $\mathbf{B}_1$. If now a current i be caused to flow through circuit No. 2 in the opposite direction to i_1, the resultant magnetic force in the iron will be

$$\mathbf{H} = \frac{4\pi n (i_1 - i)}{10 l}, \tag{25}$$

and the resultant induction will be

$$\mathbf{B} = \mu \mathbf{H}.$$

In the first expression l is the mean length of the magnetic circuit.

It is important to notice that equation (25) is only correct when the mean radius of the iron ring is great compared to its radial depth. Let the inner and outer radii be respectively r_1, and r_2, and let the thickness perpendicular to the plane of the ring be h; the flux in any circular element of radius r will then be

$$d\phi = \frac{\mu \times .4\pi n(i_1 - i)hdr}{2\pi r},$$

and the total flux, assuming μ constant, is

$$\phi = .2n(i_1 - i)h\mu \log_e \frac{r_2}{r_1}.$$

The mean value of the induction is

$$\mathbf{B} = \frac{\phi}{(r_2 - r_1)h},$$

and the true value of $\mathbf{H}$ will therefore be

$$\mathbf{H} = \frac{\phi}{\mu(r_2 - r_1)h} = \frac{.2n(i_1 - i) \log_e \frac{r_2}{r_1}}{r_2 - r_1}. \qquad (26)$$

If circuit No. 2 is opened, the induction will suddenly pass from the value $\mathbf{B}$ to the value $\mathbf{B}_1$, corresponding to the current i_1, and the total number of lines of induction cutting the test coil will be $(\mathbf{B}_1 - \mathbf{B})A$, where A is the cross-section of the iron in sq. cm. The result will be a throw S of the galvanometer, such that

$$KS = (\mathbf{B}_1 - \mathbf{B})A. \qquad (27)$$

The next reading is obtained by increasing the value of i so as to decrease $\mathbf{H}$ and $\mathbf{B}$. Circuit No. 2 is again broken and a deflection is noted corresponding to the new value of $(\mathbf{B}_1 - \mathbf{B})A$.

The constant K is determined by means of a calibrating solenoid, as explained in connection with experiment (3). The calibrating coil on the solenoid should be in series with the test coil wound on the iron ring in the same manner as in experiment (4).

The values of $\mathbf{B}$ and $\mathbf{H}$ are calculated in each case by means of equations (26) and (27); $\mathbf{B}_1$ having been previously determined by taking a reading with i equal to $2i_1$, in which case $(\mathbf{B}_1 - \mathbf{B}) = 2\mathbf{B}_1$, since $\mathbf{B}$ is negative and equal to $\mathbf{B}_1$.

Readings are obtained in a similar fashion with successively increased values of i ranging from zero to $i = 2i_1$.

From the values of $\mathbf{B}$ and $\mathbf{H}$ thus obtained, one half of the hysteresis loop may be plotted directly. The other half, being

necessarily the image of the first, may be drawn without additional readings.

The advantage of the use of a uniformly wound iron ring for magnetic measurements lies in the fact that the magnetomotive force is expended uniformly along the entire circumference L. An error is, however, introduced by the assumption that μ is the same at all points in the iron.

In order to calculate the energy loss per cycle corresponding to the plotted hysteresis loop, the area enclosed must first be measured in terms of some unit, let us say sq. cm. This area must then be expressed in terms of the coördinates **B** and **H**. As an example, let 1 cm. in terms of **B** equal 1,000, and let 2 cm. in terms of **H** equal 1. The value of a square cm. in terms of **B** and **H** will be

$$1{,}000 \times .5 = 500.$$

Let W_1 denote the area of the hysteresis loop expressed in terms of **B** and **H**. The energy lost per cu. cm. per cycle in ergs can be shown to be

$$W = \frac{1}{4\pi} W_1.$$

Method. — Calibrate the galvanometer by determining the constant K as explained in connection with Experiment 4. Since the readings from the specimen are not due to reversals of current, it will be correct to determine K by merely breaking the magnetizing current of the solenoid as in the Hopkinson Method.

Demagnetize the iron core as described above. Determine the current i_1 which when acting alone gives the maximum induction $\mathbf{B}_1$. This is done by bringing the galvanometer to rest, making $i = 2i_1$, and breaking i. The throw thus obtained should be

$$KS_1 = 2\mathbf{B}_1 A.$$

In this way, after several trials, the proper value of i_1 may be found.

During the remainder of the experiment i_1 is kept constant at the value thus determined, and the necessary readings obtained as described above. Take twelve readings so selected that they will be evenly distributed along the curve.

The determination of hysteresis does not have to be very accurate, as the hysteresis constant does not remain exactly the same, being dependent on every incident in the life of the iron. It is for this reason that hysteresis measurements by comparison with a standard having a known hysteresis constant are usually only approximate, although the determinations of permeability made in this way are quite reliable.

The equation for the ergs dissipated by hysteresis per cu. cm. per cycle,

$$W = \eta B^{1.6},$$

is not always rigidly true, since the hysteresis constant η is liable to change slightly, and the value of W is not always exactly proportional to the 1.6th power of the induction.

The determination of the hysteresis loop may also be made by the step-by-step method, where the iron core is wound with only one magnetizing coil, the current in it being varied by steps from the maximum positive to the maximum negative value. Each variation of current produces a corresponding change in the magnetic flux, which is read from the deflection of the ballistic galvanometer as already described. In this way the iron may be put through one half of a complete cycle, passing from the maximum positive to the maximum negative value of the magnetic flux, and the hysteresis loop may be constructed from the readings thus obtained.

(*b*) *Step by Step Method.* — Using the same type of specimen as in (*a*), a single magnetizing coil is employed to produce the flux. A secondary of a suitable number of turns should be wound directly around the iron. It is not strictly necessary to wind the magnetizing turns uniformly along the length of the magnetic circuit; a rectangle built up of laminations arranged so

as to break joints may be employed, with two definite coils through which the laminations are inserted. The leakage can be made very small indeed.

In carrying out the determination, the M.M.F. is put through a series of successive steps from a maximum intensity in one direction to the same value in the opposite direction; readings of the galvanometer deflection are taken corresponding to the flux changes caused by the successive M.M.F. decrements. In order to determine the maximum value of the flux, the decrements of flux during the entire half cycle are added, and the sum divided by two.

The variations of M.M.F. are conveniently obtained by connecting a resistance in series with the primary coils and arranging a number of snap switches to short circuit portions of it. A reversing switch must also be provided to reverse the current.

Method. — Close all the switches so that the maximum M.M.F. and flux are produced; then, by means of the reversing switch, change the direction of the M.M.F. a few times in order to put the iron through several magnetic cycles before taking any readings. When the galvanometer is perfectly at rest note the zero point and open the first of the snap switches so as to cut in a portion of the series resistance and suddenly diminish the M.M.F. by a definite amount. Note the deflection of the galvanometer and the ammeter reading.

Obtain the next readings in a similar manner by opening the remaining switches in succession, bringing the galvanometer carefully to rest before each observation.

The next reading is taken by reversing the current and noting the galvanometer deflection. The remaining readings are obtained by closing the various short circuiting switches one after the other and noting the galvanometer deflection and ammeter reading in each case as before.

In this manner the induction after having been first decreased by a series of steps from a positive value, for instance, is made to pass through zero and increase to the original value in the nega-

tive direction. The galvanometer deflection will not reverse at any time; this is because the flux change is always of the same sign, as an increase in negative flux will induce an E.M.F. of the same sign as a decrease in positive flux.

Calibrate the galvanometer by opening the magnetizing current of the air solenoid already described and noting the deflection of galvanometer and ammeter.

In order to calculate the values of **B** and **H**, the constant of the galvanometer being known, let S' denote one half the sum of the deflections obtained, and **H**$'$ the maximum magnetic potential gradient, then for any value $\mathbf{H}_n$ calculated from an ammeter reading,

$$\mathbf{B}_n = \frac{K}{A}[S' - (S_1 + S_2 + S_3 + \text{etc.} + S_{n-1} + S_n)]$$

where K is the galvanometer constant, A the section of iron in sq. cm., and S_1, S_2, etc., are the successive deflections.

In working with the step by step method, when a mistake is made in taking any reading, it is necessary to repeat the whole series of readings, beginning with the first.

Report. — Tabulate the readings, together with the calculated values of **B** and **H**. Plot the hysteresis loop with **B** as ordinate and **H** as abscissa. Determine its area. This may be done with a planimeter, by counting the squares in the cross-section paper, by cutting out the curve and comparing its weight with that of a known area of the same paper, or by any other convenient method. Calculate the energy lost by hysteresis in ergs per cu. cm. per cycle, in the manner already described.

Experiment 6. — Magnetic Measurements with Alternating Currents.

In dealing with laminations such as are used in the construction of armatures or transformers, a convenient commercial way of arriving at the magnetic properties of the iron is to build up a miniature transformer core out of a few of the laminations to be tested, these being arranged so that their ends overlap, forming

a closed magnetic circuit in the manner usual in the construction of transformers and as described in Experiment 4. The laminations are enclosed by two coils, a primary of few turns supplied with a low frequency alternating current, and a secondary of many turns connected to a voltmeter. The impressed E.M.F. should be sinusoidal.

The magnetizing current is read by an ammeter or dynamometer, and the maximum flux density corresponding to it is obtained from the reading E of the voltmeter by means of the equation

$$\mathsf{B} = \frac{E \times 10^8}{\sqrt{2}\pi n f A}, \tag{28}$$

where A is the section of the iron in sq. cm., and n the number of secondary turns.

A wattmeter is employed to measure the energy loss, its current coil being in series with the ammeter and the magnetizing coil on the specimen. The pressure coil of the wattmeter may be connected to the secondary coil about the specimen. In this case, however, the energy dissipated in the circuit of the pressure coil must be subtracted from the wattmeter reading. It is also possible to use as the source of power a transformer with two secondary windings, one supplying the magnetizing current to the specimen at a low voltage, and the other energizing the pressure coil of the wattmeter at the rated voltage of that instrument; here, however, the reading of the wattmeter must be diminished by the value of the i^2r losses in the magnetizing circuit of the specimen, including the current coil of the wattmeter and the ammeter. The energizing transformer should in this case be of sufficient size so that it will furnish the current required by the specimen without appreciable regulation losses.

In each of the methods described the reading of the wattmeter must be divided by the ratio of turns before the subtraction mentioned is made; in the first case the ratio of turns between the primary and secondary windings on the specimen must be

taken, and in the second case, the ratio of turns of the two secondary coils of the energizing transformer.

In order to eliminate the effect of eddy currents, several readings of the instruments should be made at successively smaller values of the frequency, beginning at about 12 cycles per second as a maximum, the value of the induction being kept constant. By plotting the values of current and ergs per cu. cm. per cycle obtained from these readings with respect to frequency as abscissa the curves obtained may be prolonged until they cut the *y* axis, thus giving the true values, exclusive of the influence of eddy currents. It will be found, however, that frequencies of less than 9 cycles per second give nearly correct results without correction.

Since the wattmeter readings give the joules per second, the value of η is given by the equation

$$\eta = \frac{\text{watts} \times 10^7}{\text{c.c.} \times f \times B^{1.6}}. \tag{29}$$

The reading of the ammeter gives the effective current corresponding to a sinusoidal wave of magnetic induction whose maximum value is given by equation (28). The magnetic intensity **H** may be found by multiplying the current by $.4\pi n$ and dividing by the mean length of the magnetic circuit.

Care should be taken that the voltmeter employed is sensitive enough so that the current taken by it does not alter the value of the ammeter reading. In order to eliminate this source of error completely it is possible to balance the voltage from the test coil on the specimen against a known fraction of the generator volts, using a telephone receiver as an indicator as in the well-known method of curve tracing by instantaneous contact.

Since the impressed wave of E.M.F. at the primary terminals must be sinusoidal in order to comply with equation (28), it is evident that it is absolutely necessary in this method to regulate the voltage without the insertion of resistance or reactance in the magnetizing circuit, which always distorts the voltage wave at the terminals of the primary coil.

Method. — At a frequency of 8 cycles note the instrument readings at 10 values of the induction between 10,000 and 1,000. With **B** = 10,000 take readings at frequencies of 12, 10, 8 and 6.

Report.—Plot curves with ergs per cu. cm. per cycle and the values of **H** as ordinates and **B** as abscissa.

Construct also a curve with calculated values of η as ordinates and f as abscissa. By prolonging it through the vertical axis determine the true value of η.

Experiment 7. — Measurement of Hysteresis with the Ewing Hysteresis Tester.

The instrument consists of a pivoted horseshoe magnet carrying a needle which moves along a graduated scale. Gravity tends to maintain it in the zero position. Between the poles of this magnet the specimen to be tested is rotated. This is made of a number of rectangular laminations bound together, and its axis of rotation is coincident with that about which the magnet is pivoted. As the specimen revolves, its magnetic flux passes through complete magnetic cycles, but owing to the magnetic lag, or hysteresis, the lines of induction tend to stay in the specimen after passing the pole pieces. The result is that, when a specimen having hysteresis is rotated, it tends to drag the pivoted magnet along with it and produce a deflection of the needle.

Let W_h be the energy lost by hysteresis per cu. cm. per cycle at N revolutions per minute. Neglecting eddy currents and friction, the work done per minute in revolving the specimen will be

$$W = W_h \times N \times \text{c.c.} \tag{30}$$

As already explained, as the specimen revolves it drags the magnet out of its position of equilibrium, causing a deflection which will be a measure of the counter torque **T** against which the specimen is being turned. Therefore,

$$\mathbf{T} = K\theta.$$

The work W, however, is also equal to the counter torque **T**

multiplied by N, the number of revolutions per minute; that is,

$$W = \mathrm{T}N = K\theta N. \tag{31}$$

By combining equations (30) and (31) we have

$$W_h = K_1\theta.$$

This value is independent of the speed.

K_1 is not a constant, but depends on θ. In other words, twice the hysteresis loss does not necessarily produce twice the deflection.

The above is based upon the assumptions that, in any specimen, the hysteresis loss per cu. cm. per cycle is a constant for a given maximum induction, and that the work lost through eddy currents is negligible.

In order to determine W_h for any unknown specimen, it is necessary to calibrate the hysteresis tester. This is done by means of two standard specimens whose hysteresis losses are known, having been previously determined by some other method.

Let W_a and W_b be the losses per cu. cm. per cycle, and θ_a and θ_b the corresponding deflections produced by the two standard specimens when rotated in the instrument. Plot the values of W_a and W_b on cross-section paper with respect to θ as abscissa and W as ordinate, drawing a straight line between the points.

The values of θ_a and θ_b should not be widely different from each other, and if they are not, the curve between W_a and W_b will be a straight line. This line is the calibration curve of the hysteresis tester, and by means of it, it is possible to determine W_h for any unknown specimen.

Method. — Determine the calibration curve, as above described. Rotate each of the specimens to be tested, and note the deflections obtained. Lay off these deflections as abscissæ on the calibration curve sheet. The intersections of the corresponding ordinates with the calibration curve will give the required values of hysteresis loss per cu. cm. per cycle for the different specimens tested.

In performing the tests, the speed of rotation should be just

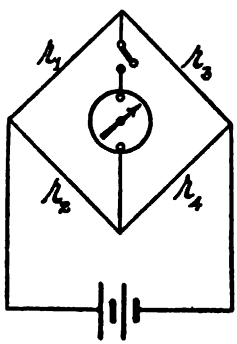
great enough to give a steady deflection. If the speed is too high the air currents produced by the rapid motion of the specimen will tend to increase the deflection above the correct value.

Report. — Plot the calibration curve as described, and tabulate the values of W_h and θ obtained for all the specimens tested.

Experiment 8. — Determination of Resistance with a Wheatstone Bridge.

Fig. 94 represents the diagram of connections of a Wheatstone Bridge. One unknown resistance can be measured by this arrangement in terms of three known resistances. The exact combination of the resistances is obviously of no consequence as far as the principle of the bridge is concerned. It is always possible to adjust the resistances so that the drop in r_1 equals that in r_2. In that case there will be no current in the circuit of the galvanometer. Then

Fig. 94.



$$\frac{r_1}{r_2} = \frac{r_3}{r_4} \quad \text{and} \quad \frac{r_1}{r_3} = \frac{r_2}{r_4}.$$

A current will, however, flow from the battery through each side of the bridge, and the current in the battery is necessarily equal to the sum of these currents. We have therefore

$$i = i' + i'',$$

and

$$E = i'(r_1 + r_3) = i''(r_2 + r_4).$$

In order to avoid all risk of injuring the resistance coils it is customary to use dry cells or other primary batteries in connection with the bridge. The result of this is that if the resistances are all small, the voltage across the bridge, and therefore the accuracy of the measurements may become greatly diminished. On the other hand if the resistances in the bridge are very high and comparable to that of the galvanometer, the sensi-

tiveness will be diminished because the per cent. of unbalancing must be quite great in order to produce an appreciable deflection.

If r_4 is the unknown resistance, r_1 and r_3 are said to be the ratio arms of the bridge, and their relation may be arbitrarily decided on. A balance is then obtained by adjusting r_2 until the galvanometer fails to deflect. If r_1/r_3 equals unity it will usually be found that the subdivision of the resistances in r_2 is not sufficient to obtain an accurate balance. This difficulty is obviated by changing r_1/r_3 in such a way as to increase the required value of r_2. The principal consideration which limits the extent to which this can be pushed is that the increase of r_2 diminishes the sensitiveness.

In accurate bridge measurements care should be taken to correct the values of the resistance for temperature variation, and in any case it is necessary to be sure that the plugs are all clean and making good contact. A good way of securing this last condition is by turning the plugs around when inserting them. This will be found to give better results than simply forcing them in tightly.

Method. — Of the three adjustable resistances the ratio arms are the two which have the fewest subdivisions, while the third is frequently subdivided to less than $\frac{1}{1000}$ of its maximum value.

In making a determination, the unknown resistance being r_4, balance the bridge as closely as possible with the ratio arms r_1 and r_3 equal. Having thus found the approximate value of r_4 select the ratio of r_1 to r_3 that will give the desired degree of accuracy. By thus making the measurement with two ratios, the possibility of a serious error is greatly diminished.

Do not accept zero deflection as a sign that the bridge is balanced, but make sure by trial that increasing or decreasing r_2 will give deflections in opposite directions.

In connection with this experiment, when using a Thomson galvanometer, unbalance the bridge slightly so as to obtain a small permanent deflection; then adjust the controlling magnets about the galvanometer so as to make this deflection greater,

thus increasing the sensitiveness of the instrument and consequently the accuracy of the determination. If the unknown resistance is inductive, care should be taken to keep the battery key closed long enough for all the currents to become constant before closing the galvanometer key.

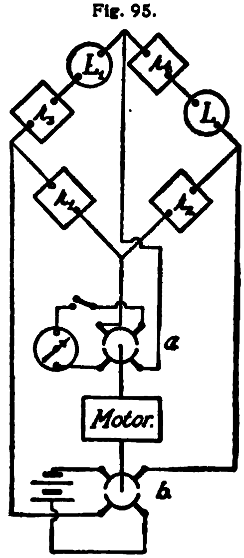
Determine the value of the resistance with three different ratios.

Report. — Tabulate the values obtained together with the ratios employed. Describe the connections, the apparatus used and the method of making the determination.

Experiment 9. — Determination of Inductance and Capacity with a Secohmeter or with an Alternator.

(*a*) *Determination of Inductance.* — The apparatus, illustrated in Fig. 95, consists of a Wheatstone bridge in which the two ratio arms r_1 and r_2 are non-inductive resistances so subdivided that the ratio can readily be altered by small percentages, while the third arm contains an adjustable standard of self induction L_1 in series with a variable non-inductive resistance r_3, the fourth arm containing the unknown inductance L in series with a variable non-inductance resistance r_4.

Fig. 95.



The standard inductance may be made of two coils in series, one pivoted inside the other. The value of this inductance will evidently depend on the angle which the two coils composing it make with each other. The movable coil carries a pointer which moves over a scale graduated in henrys. The rest of the apparatus consists of the battery, the galvanometer and a secohmeter.

The secohmeter consists of a small constant speed motor which carries a pair of two part commutators *a* and *b*. These are both mounted on the shaft, and should be set so that the reversal of the current takes places at the same instant in each case.

The commutators are connected in the battery circuit and in the galvanometer circuit so that when the motor is running the battery current reaches the bridge as an alternating current, while the current passing from the bridge to the galvanometer is rectified.

In this arrangement the essential principle is that means are provided for first supplying the bridge with direct current, and then with alternating; also, an indicating instrument is provided and adapted so that the bridge balance may be detected by it under both conditions. It is obvious that the apparatus described may be considerably modified. For instance, a telephone receiver may be used to observe the A.C. balance, and when it is desired to balance with D.C., a galvanometer may be substituted for the telephone by means of a double throw switch; also, instead of using commutators to furnish alternating currents when in motion and direct when at standstill, a double throw switch may be provided which will connect the battery terminals of the bridge either to a D.C. or to an A.C. source, as desired.

In what follows it will be assumed that the commutators for battery and galvanometer currents are employed, as in the usual form of the secohmeter.

In making the determination, select some relation r_1/r_2 of the ratio arms of the bridge; the value selected depending upon a rough estimate of the relative values of the known and unknown inductances. With the motor standing still, balance the bridge for resistance by means of the variable resistances in the other two arms. The inductances have no effect, owing to the fact that the commutators are not rotating. When the galvanometer does not deflect

$$\frac{r_1}{r_2} = \frac{r_3}{r_4} \qquad (29)$$

r_3 and r_4 being the total resistances of the branches containing the standard L_1 and the unknown inductance L, respectively.

Start the motor. The current received by the bridge will now be alternating, and on closing the galvanometer key there will

in general be a deflection, unless it should happen by chance that

$$\frac{r_1}{r_2} = \frac{\sqrt{\omega^2 L_1^2 + r_3^2}}{\sqrt{\omega^2 L^2 + r_4^2}}, \tag{30}$$

which is the condition for a balance with alternating current.

If, as will naturally be the case, there is a deflection, alter the value of L, so as to bring the galvanometer to zero, when equation (30) will be satisfied. This will always be possible provided that

$$\frac{r_1}{r_2} < \frac{L_1}{L}.$$

Equation (30) is only rigidly applicable when the current supplied to the bridge is sinusoidal, ω being equal to 2π multiplied by the frequency. The alternating current produced by the two part commutator, however, is a complex harmonic, being made up of a considerable number of sine waves of different frequencies. The deduction based on equation (30) will, nevertheless, hold good because the equation is true for each of the sinusoidal components of the current.

By means of equations (29) and (30) we may write equation (31) in the form

$$\frac{r_1^2}{r_2^2} = \frac{\omega^2 L^2 + \frac{r_1^2}{r_2^2} r_4^2}{\omega^2 L^2 + \frac{r_2^2}{r_1^2} r_3^2}, \tag{31}$$

whence

$$\omega^2 L^2 r_1^2 + r_2^2 r_3^2 = \omega^2 L_1^2 r_2^2 + r_1^2 r_4^2;$$

and since

$$r_2^2 r_3^2 = r_1^2 r_4^2$$

we have

$$\frac{L_1}{L} = \frac{r_1}{r_2}. \tag{32}$$

If it is found impossible to balance L with even the maximum value of L_1, it is evident that the value of the ratio r_1/r_2 is too large,

and a smaller ratio must be chosen. The bridge must then be balanced for resistance, as before, with the commutators stationary, so as to fulfill equation (29). After this, rotate the commutators, and attempt to fulfill equation (30) and consequently equation (32) by varying L_1. When this is successfully accomplished there should be no deflection of the galvanometer whether the commutators are rotating or not.

In this experiment, increasing the frequency increases the possible accuracy of the determination by making the E.M.F.'s of self induction greater.

Method. — With the commutators stationary, balance the bridge for resistance, the ratio r_1/r_2 having been chosen with reference to the estimated relative values of L_1 and L.

Rotate the commutators and try to bring the deflection of the galvanometer to zero by adjusting L_1. If this is found to be impossible, select another value of r_1/r_2 and repeat the entire operation. Continue in this way until the desired result is attained.

Care should be taken that the commutator brushes do not rest on the insulation between segments when balancing for resistance, thus making an open circuit. It is also important that the brushes on each of the commutators should have the same relative position with respect to the segments, as this increases the sensitiveness, and therefore the accuracy of the determination.

(*b*) Determination of Capacity.

Leaving all the connections as described, substitute a known capacity C_1 for L_1 and r_3, and put the unknown capacity C in place of L and r_4. When the commutators are stationary the galvanometer cannot deflect, since direct current cannot pass through either of the condensers. When the commutators are rotated, however, there will be a deflection of the galvanometer, unless by accident the impedances of the four branches should happen to fulfill the condition for zero deflection which is

$$\frac{r_1}{r_2} = \frac{\frac{1}{\omega C_1}}{\frac{1}{\omega C}} = \frac{C}{C_1}. \tag{33}$$

The resistance reaction is assumed to be zero in the branches containing the capacities.

Method. — Rotate the commutators and adjust the ratio r_1/r_2 until there is no deflection of the galvanometer. Equation (33) will then be fulfilled and the value of C can be calculated from it.

Experiment 10. — Calibration of a Thomson Recording Watt-hour Meter.

This meter is a direct-current motor with a high resistance armature and low resistance field.

The high resistance armature is connected in series with an additional high resistance across the potential difference at the terminals of the supply circuit in which the power developed is to be recorded. On account of the high resistance, the counter E.M.F. of the armature is negligible compared with the *ir* drop, and the armature current is therefore directly proportional to E, the line volts, and practically independent of the speed of the motor.

The low resistance field winding is connected in series with the line so as to carry the full current supplied. There is no iron in the construction of the meter, and the field flux is therefore directly proportional to the current I.

The torque $\mathbf{T}_1$ impressed on the motor shaft is the product of field flux and armature current as in the case of all shunt motors, hence

$$\mathbf{T}_1 = K_1 IE. \tag{34}$$

It is evidently necessary for the proper operation of this meter that the speed shall be proportioned to the watts, and consequently to $\mathbf{T}_1$, the impressed torque. This is accomplished by the following simple means :

The friction of the bearings is made very trifling and a copper disc is mounted on the rotating shaft. This copper disc rotates between adjustable permanent magnets. The result is that eddy currents are set up in the rotating disc, and these eddy currents produce the retarding torque $\mathbf{T}_2$ which limits the speed of the meter. If N is the speed in revolutions per minute

$$\mathbf{T}_2 = K_2N, \tag{35}$$

because the eddy currents are proportional to the speed. But for constant speed,

$$\mathbf{T}_1 = \mathbf{T}_2, \text{ or } IE = KN. \tag{36}$$

It is evident, therefore, that if there were no friction, the relation between N and IE would be practically a straight line, and the factor of proportionality K would be really a constant throughout the entire range of the instrument. As a matter of fact this is only true when the watts are sufficiently great to make the effect of friction imperceptible. At very light loads K increases, and is infinitely great at the instant of starting unless some corrective is employed. This is usually provided in the form of a small auxiliary field coil connected in series with the armature and adjusted so that the torque due to it almost exactly counteracts the retarding torque of friction.

The danger of any such modification lies in the fact that if the adjustment of the auxiliary field is incorrect the movable member of the meter is liable to rotate slowly when no energy is being supplied to the consumer.

Method. — Connect a standardized ammeter and voltmeter in such a way that the product of their readings will give the watts of a D. C. supply circuit. Those watts, as already explained, should be proportional to the speed of the meter. See equation (36). Note the values of I, E and N at about twenty-five successively greater values of the power, and calculate K in each case from equation (36).

Report. — Determine a curve with values of N as ordinates

and watts as abscissæ. Plot also upon the same sheet and with the same abscissæ a curve having values of K as ordinates. Tabulate also the readings obtained and the values calculated.

Experiment 11. — Calibration of a Siemens Dynamometer and an Ammeter by Means of a Kelvin Ampère Balance.

The ampère balance, as its name implies, is an instrument in which the magnetic pull due to a current in a coil of wire is balanced against the attraction of gravity. The current is determined by the method of weighing. As this operation is one of the most accurate of physical measurements, the ampère balance is an inherently accurate instrument.

The balance consists of a pivoted horizontal bar with a coil at each end. Each of these coils is between two fixed coils of similar shape mounted one above and one below it. All of the six coils are connected in series in such a way that when the current flows, one of the movable coils is pulled upwards, and the other downwards. The effect of the current is, therefore, to produce a turning moment and consequently a deflection of the balance arm. This deflection is counteracted by a small weight or slider which may be moved along a graduated bar. The current will therefore be measured in terms of the distance through which the weight must be moved in order to effect a balance.

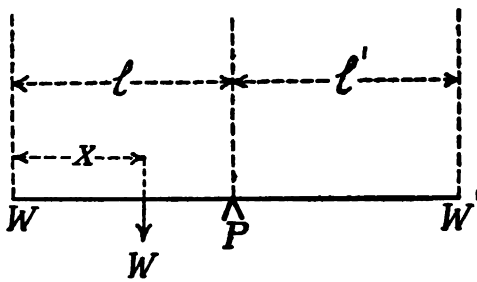


Fig. 96.

Fig. 96 shows the graduated arm, the point P being the center of moments. The middle weight W represents the slider. W' is the corresponding weight which is placed in a pan on the right hand end of the graduated arm in order to balance the weight of the slider when it is in its zero position at the extreme left end of the scale.

When no current is passing, W being at zero, the condition for a balance is

$$Wl = W'l'. \tag{37}$$

When current flows, however, an additional moment is produced which will move the arm in an anticlockwise direction. The slider W must be moved to the right a distance x in order to produce a balance. As before, the necessary condition of equilibrium is that the algebraic sum of the moments about P must be zero.

The moment due to the current depends upon the magnetic pull between the fixed and movable coils, and since the coils are all in series, it is evident that doubling the current will give four times the turning moment. If the strength of two electromagnets is made twice as great they will evidently attract or repel each other four times as strongly. It is plain, therefore, that the turning moment is proportional to the square of the current producing it.

When a current is flowing, therefore, the required condition for a balance is

$$W(l - x) = (W'l' + K_1 i^2). \tag{38}$$

Combining this with equation (37) we have

$$Wx = K_1 i^2,$$

and

$$i = K\sqrt{x}.$$

The ampère balance is equally correct for direct or alternating currents. In the latter case i is the "effective" value of the current.

Alternating current ammeters are usually graduated to give the current readings directly in ampères. This, however, is not true of the Siemens dynamometer. That instrument consists of two coils, one fixed and the other movable; their planes being at right angles when in the zero position. The two coils are connected in series so that the turning moment due to a current flowing through them is, as in the case of the ampère balance,

proportional to the square of the current. The movable coil carries a pointer, and the coil is connected to a torsion head by means of a supporting filament and a fine spiral spring. This torsion head also carries a pointer which moves around a circular scale graduated in degrees. When current passes, the movable coil is deflected, and its pointer is brought back to zero by turning the torsion head through a certain number of degrees in the opposite direction. The necessary number of degrees is proportional to the turning moment, and therefore to the square of the current. Hence

$$i = K\sqrt{\theta}.$$

The factor of proportionality, K, is never absolutely constant throughout the entire range of the instrument, and a calibration curve is necessary in using the dynamometer.

Method. — A number of current reading instruments may be calibrated at the same time by connecting them in series with the ampère balance. By means of the balance determine the true current corresponding to each of the instrument readings. Take twenty readings differing from each other by approximately equal increments of current. Care should be taken in the case of the dynamometer and the balance to see that these instruments read zero for zero current. This should be looked after not only at the beginning of the calibration but also after every two or three readings.

The range of the balance may be altered by changing the weights used, thus changing the constant K.

The sensitiveness of the instrument may be altered by raising or lowering some brass weights which travel vertically along threaded spindles mounted above the center of moments.

The balance arm should be raised off its supports after using. It should be noticed that these supports are not knife edges, but ribbons made of very fine copper wires.

The zero point of the instrument may be adjusted by changing the relative weights of the two sides of the balance. This is done either by means of a sliding weight or by moving a small brass

strip, carried by the balance arm, either to the right or to the left.

The zero point of the Siemens dynamometer may be adjusted by moving the torsion head and pointer with respect to the spiral spring. The latter is connected to the torsion head by a collar which is kept from slipping by a screw which holds it tight.

Report. — Plot the results relating to each instrument on a separate curve sheet.

In the case of an ammeter there should be a calibration curve having instrument readings as abscissæ and true ampères as ordinates, also two curves drawn with respect to the same abscissæ giving the absolute and the per cent. errors.

The curve sheet relating to the dynamometer should contain a calibration curve with instrument readings as abscissæ and true ampères as ordinates, and a curve showing the values of K with respect to the same abscissæ.

Experiment 12. — The Potentiometer. (a) Calibration of a Voltmeter; (b) Calibration of an Ammeter; (c) Measurement of a Resistance.

The potentiometer is an instrument used for measuring and comparing differences of potential. The unknown E.M.F. or a frac-

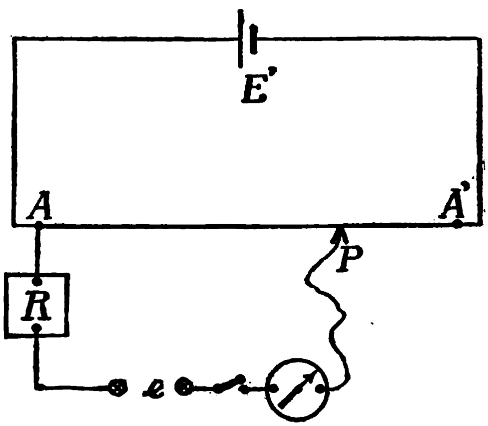


Fig. 97.

tion of it is connected in series with some known constant voltage through a high resistance and a galvanometer. The direction of these two E.M.F.'s is, however, reversed, so that, when they are equal there will be no deflection of the galvanometer on closing the key. It is evident that by this arrangement a very small per cent. difference between the E.M.F.'s may be able to produce a noticeable deflection.

For commercial use the potentiometer is usually arranged in some compact and convenient form. All of the different types, however, embody the same fundamental features. Fig. 97 shows the principle in its most simple form. In this diagram, AA' is a slide wire of several ohms resistance stretching along a graduated scale and the point P is a sliding contact. The two E.M.F.'s to be compared are connected, the larger one at E', and the smaller at e; care must be taken in doing this to connect them in such a way that the E.M.F. at e will oppose the drop caused by the current from E' along the length AP of the wire. In order to find the relation between E' and e the position of the slider P is adjusted so that there is no current through the galvanometer and no deflection, which can only be the case when e is exactly equal and opposite to the drop over AP. The relation between E' and e at zero galvanometer deflection is given by the equation

$$E' = e \times \frac{AA'}{AP},$$

from which either of the E.M.F.'s e or E' may be found, provided the other is known.

In obtaining a balance, the resistance R must be maintained high, and it should be at least 100,000 ohms if a standard cell is connected at e. When an approximate balance has been obtained, R may be short circuited temporarily in order to attain a high degree of accuracy.

In using the potentiometer for the calibration of a voltmeter the instrument to be calibrated may be connected in parallel with E' across the resistance AA', and a standard cell connected at e; then by giving E' different values and determining it each time

by balancing the potentiometer as described, the true volts may be found corresponding to the various voltmeter readings.

It will be readily seen that where the voltage to be measured in this way is high, it is necessary that the resistance AA' shall be sufficiently high to prevent heating, and it may be wound upon a tube with means for permitting the contact point P to travel along its length. When a balance has been obtained, the value of E' can always be determined in terms of the standard cell and the ratio AA'/AP.

If the E.M.F. to be measured is very small, and less than that of the standard cell, the voltage E' may be held constant at any convenient value; the unknown voltage may then be compared with the standard by connecting each of them in succession at e and balancing the potentiometer; the ratio of the known and unknown voltages will be the same as that of the corresponding values of AP.

(*a*) *Calibration of a Voltmeter.*

Method. — Connect the voltmeter to the terminals AA', and adjust the potentiometer resistance to a suitable value, depending upon the range of the instrument to be calibrated, in order to prevent overheating. Connect the standard cell at e, with R at its full value. Adjust E' to about one-tenth of full scale voltage, and obtain a balance by finding the position of the point P at which the deflection of the galvanometer becomes zero. Be sure that the deflection reverses as the slider is moved from one side of the zero position to the other. When an approximate balance has been found, short circuit the resistance R, and make the determination as accurately as possible. Note the ratio AA'/AP, and the voltmeter reading.

Repeat this operation with ten successively greater values of E'.

Calculate the value of the true volts corresponding to each instrument reading by multiplying the voltage of the standard cell by the ratio AA'/AP in each case.

If it is necessary to make a determination at a voltage lower than that of the standard cell, adjust E' to a slightly higher value,

and keep it constant. Connect the voltmeter at e, and keeping R at its highest value, produce the required reading by connecting an adjustable E.M.F. across the terminals of the voltmeter. Balance the potentiometer as before, and note the resistance AP and the voltmeter reading.

Remove the voltmeter and auxiliary E.M.F., and connect the standard cell at e, keeping E' constant. Balance the potentiometer, and note AP. Calculate the true volts corresponding to the voltmeter reading by multiplying the voltage of the standard by the ratio of the two values of AP. If there are several points on the voltmeter scale to be calibrated in this way it is only necessary to obtain the balance with the standard cell once, since E' is assumed to be maintained constant.

(*b*) *Calibration of an Ammeter.*

Method. — In this operation a standard resistance is placed in series with the ammeter. The value of the standard resistance should be such that, with the current for a full scale ammeter reading, the drop across it shall be about of the same order as the voltage of the standard cell.

Two wires from the terminals of the standard resistance are then connected to e. The drop across the standard resistance is then determined by means of the potentiometer for twenty different values of the current. The true current values corresponding to the various ammeter readings are obtained by dividing the measured drops by the value of the standard resistance in ohms.

In this determination also, the slide wire must be calibrated by means of the standard cell.

(*c*) *Measurement of a Resistance.*

Method. — Connect the unknown resistance in series with a known standard resistance of about the same value. The same current will then flow through both, and the resistances will be to each other directly as the voltages across their respective terminals. Measure the two drops by connecting them successively

to e. Find the value of the unknown resistance from the following equation,

$$R_x = R_1 \frac{E_x}{E_1}.$$

Determine R_x for three values of the current.

In this determination it is not necessary to calibrate the slide wire as in (*a*) and (*b*); E_x and E_1 may be expressed in terms of scale divisions instead of volts.

Report. — In (*a*) and (*b*) construct curves with instrument readings as abscissæ and true volts, or ampères, as ordinates. On the same curve sheet, in each case, plot the absolute and per cent. errors in the form of curves, taking the instrument readings as abscissæ.

Experiment 13. — Determination of the Efficiency of a Lead Storage Battery.

By the expression "efficiency of a storage battery" is meant the ratio between the watt-hours output and the watt-hours input required to restore the battery to the same charged condition as it was in, at the beginning of the discharge. This ratio is, moreover, specifically defined as the watt-hour or commercial efficiency.

In practice, before proceeding with a storage battery test it is customary to determine the number and linear dimensions of the plates and of the containing vessel, the weight of the plates, of the electrolyte and containing vessel, the battery being preferably in a fully charged state. After the completion of a long series of tests, the battery should be weighed again, in same condition of charge, as a whole and in detail, so as to detect any change in the weight of the plates, thus aiding in the determination of the rate of disintegration and the probable life of the battery.

When a battery has been finally set up and made ready for test, it should be brought to a fully charged condition, the collective indications of which are as follows:

(*a*) The terminal E.M.F. becomes approximately 2.5 volts, depending upon the rate of charge, *i. e.*, at low rates it will be

slightly less than this and at rates greater than the normal or eight hour rate it will be somewhat higher, remaining, however, constant after the charge is completed.

(*b*) The density of the electrolyte (as measured by hydrometer) increases gradually and finally becomes constant at about 1.2 specific gravity, unless the charge rate is so excessive that the water present is rapidly decomposed. It is advisable to employ a lead weighted hydrometer in preference to a mercury one, since the breakage of the latter will introduce mercury into the cell, thus producing destructive local action and internal discharge. The electrolyte should be agitated before hydrometer readings are taken, so as to have the density uniform throughout.

(*c*) Excessive formation of gases at the plates, showing a complete oxidation of the positive active material and a complete reduction to spongy lead of the negative active material.

(*d*) The active material on the positive plate turns a dark brown or chocolate color; a blackening of this material indicates an overcharge.

(*e*) The active material on the negative plate turns a dark slate color.

(*f*) Cadmium, when immersed in the electrolyte of a lead storage battery, gives reliable indications of the potential of the positive and negative plates with respect to itself. Readings are taken by inserting the cadmium stick (connected to one terminal of a voltmeter) into the electrolyte, and connecting the other terminal of the voltmeter first to the positive plate and then to the negative plate. If the battery is in proper condition and fully charged, the voltmeter deflections as caused by the respective potential differences, will be nearly 2.5 volts for the positive plate and nearly zero for the negative plate. (Slightly negative in the case of pasted plates and slightly positive in the case of formed plates.)

Thus, in preparing a cell for test, it should be charged at the normal rate until the above stated "full charge" conditions are obtained.

The next step is to discharge the cell at a *constant* current rate (usually the normal or 8 hour rate), until its terminal voltage has decreased to 1.8 volts; during this discharge, the terminal volts, temperature, specific gravity of the electrolyte and cadmium voltages should be noted at fifteen minute intervals. If on discharge the potential difference between the negative plate and the cadmium stick reaches .25 volts, before the cell voltage falls to 1.8, the discharge should be considered as ended. Should this occur on more than one discharge, either local action or insufficient capacity of the negative plates is indicated.

If the discharge rate is about twice the normal, the terminal voltage on discharge should be about 1.7, and if the rate is four times the normal (*i. e.*, the one hour rate), the terminal volts on the completion of discharge should be 1.6. After the discharge is completed, the cell should be recharged, preferably at the same current value as on discharge, the terminal volts, cadmium volts, specific gravity and temperature values being noted at fifteen minute intervals. When the various readings indicate a practically completed charge, the charging current should be reduced to about one half the normal, and as soon as the voltage, specific gravity, etc., become constant, the charging should be discontinued.

Report. — Plot curves with terminal volts, cadmium volts, specific gravity, etc., as ordinates, and time as abscissa. The average terminal volts in any instant can be obtained from the corresponding voltage curves, by determining the area enclosed by it and dividing by the length of the base line. This average voltage multiplied by the ampères-hours will give the corresponding watt-hours. The watt-hours thus derived from the discharge voltage curve divided by the watt-hours similarly obtained from the charging curve will give the true battery efficiency or

$$\frac{\text{Watt-hours on discharge}}{\text{Watt-hours on charge}}\,100 = \text{per cent. efficiency.}$$

The ampère-hour efficiency is the ampère-hour output divided by the ampère-hour input, and it is higher than the watt-hour

efficiency on account of the difference in voltage during charge and discharge. In fact the ampère-hour efficiency is of little practical value since the difference in voltage on charge and discharge may be so great as to reduce the commerical or watt-hour efficiency to an extremely low quantity, while the ampère-hour efficiency may still be high.

The determination of the efficiency of a storage battery may be very misleading, inasmuch as the value obtained depends to a considerable extent on the previous treatment to which the battery has been subjected, and is not by any means a practically fixed quantity as is the case with machinery. A new battery will often show a low efficiency quite different from that obtained after a few additional cycles of discharging and charging; in fact, any reliable determination of efficiency should be the result of a *series* of tests similar to that already described. A simple set of connections for battery testing is shown in the following diagram.

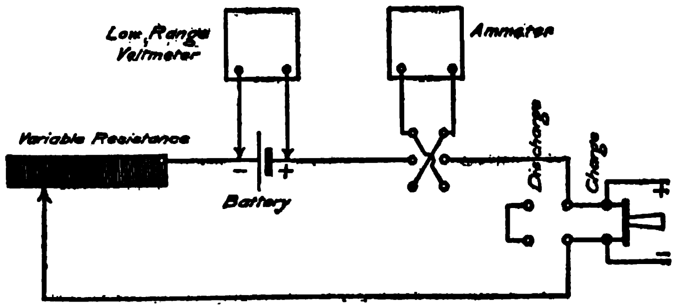


Fig. 98.

Experiment 14. — Charging at Constant Potential.

Beginning with the battery discharged, close the line switch and charge the battery, keeping the impressed voltage constant. Read the current every five minutes for the first fifteen minutes and then every quarter of an hour for forty-five minutes longer. It will be found that the current diminishes at first very rapidly and then more gradually. This is due to the fact that the counter E.M.F. increases and cuts down the current.

Report. — Plot the current readings in the form of a curve having ampères as ordinates and time in minutes as abscissa.

Experiment 15. — External Characteristic Curve of a Storage Battery.

With the battery partially charged, the line switch being open, close the discharge circuit long enough to take a reading of current and terminal E.M.F. Repeat this operation, changing the external resistance each time so as to get a different current. Take fifteen readings between zero and 150 per cent. of the normal current of discharge.

Plot the results in the form of a curve with ampères as abscissæ and terminal volts as ordinates. This curve, which is the external characteristic of the battery, will be found to be almost a straight line, showing that the internal resistance is pretty nearly independent of the load for a given condition of the battery. From the slope of this line calculate the resistance of the battery. If an increment of current, Δi, produces a drop in volts, Δe, the internal resistance of the battery is

$$r = \frac{\Delta e}{\Delta i}.$$

Experiment 16. — Storage Battery Inspection.

Method. — At the same hour each day for one week take the necessary readings to fill out the accompanying blank. In the space headed " Remarks " put down anything unusual in connection with the work which the battery is or has been doing, its general condition, attention required, etc. Make the remarks as full as possible.

No other report will be required in connection with this experiment.

STORAGE BATTERY DAILY INSPECTION REPORT.

Electrical Laboratory.

..................................A. M.
Time
..................................P. M.

At..

Consisting of....................................Cells, Type.............................. ....

(Charging)
Battery (Discharging) at..ampères. (Voltage

readings to be taken with current flowing, preferably at end of charge; gravity readings immediately after.)

Battery has been (Charging / Discharging) for..hours,
at average rate of..ampères.
Cells (Nos. ......) especially worked on during previous day.....................................
Height of Electrolyte above top of plates...inch
Water was added to replace evaporation...(Date)
Temperature of Electrolyte......F.; of Air of Battery Room......F.

Date. Time. Date. Time.

Cell.	Cadmium. Pos.	Neg.	Volts.	Sp. Gr.	Cell.	Cadmium. Pos.	Neg.	Volts.	Sp. Gr.
1					1				
2					2				
3					3				
4					4				
5					5				
6					6				
7					7				
8					8				
9					9				
10					10				
11					11				
12					12				

Remarks:
Readings taken by..
" approved by..(in charge of work)

Experiment 17.—Determination of Candle Power.

The candle power of a source of light along a given direction means the amount of light per unit solid angle in the given direction divided by the amount of light per unit solid angle in the same direction issuing from a unit source of light. In other words, the candle power of a source of light is its intensity along a given direction expressed in terms of the intensity of light from the unit source along the same direction. Consequently, when we say that the horizontal intensity of a lamp is 16 candle power, we mean that the flux of light per unit area at any distance is sixteen times what it would be if the source were a unit of light.

In measuring candle power, the lamp to be tested is placed at

one end of the photometer and the standard at the other. In testing a number of lamps it is customary to compare them with an incandescent lamp which has been standardized by comparison with some fundamental standard of light, as a standard candle or an amyl-acetate flame. The object of this is to facilitate the work, as the similarity of color between the secondary standard and the lamps to be tested makes the measurements more accurate, as well as rapid. The secondary standard should be standardized and used a little below its rated candle power; it will then last much longer without change. This lamp must always be used in the same position as that in which it was standardized. The horizontal candle power of an incandescent lamp varies a little in different directions; it is, therefore, desirable to determine the candle power of a lamp while it is rotating rapidly. Most photometers are fitted with a device for doing this. The next best way of testing the lamps is to turn each one about its vertical axis so that its candle power is a maximum, and make the measurement with the lamp in that position; if the filaments are of the same form, this will at least afford a comparison of one lamp with another.

Method. — Standardize an incandescent lamp by means of an amyl-acetate burner. During this operation the gas flame must be maintained carefully at the right height, the wick having been smoothly trimmed before beginning the test. Make a mark upon the incandescent lamp to indicate the position in which it has been standardized. Maintain the voltage constant, and below the rated value by about 4 per cent.

Using this lamp as a secondary standard, place it in the position, and energize it with the voltage corresponding to its standardization; then determine the candle power of five unknown lamps by means of it. All the lamps under test must be held at constant rated voltage, and the current noted by an ammeter in series.

It is extremely important in these tests to hold the voltage constant, as a change of 1 per cent. in the impressed volts may cause a change of more than 5 per cent. in the candle power.

Connect an ammeter in this circuit and note the ampères taken by each lamp.

Report. — Calculate the watts per candle in the case of each lamp. Plot the results on a sheet of cross-section paper with watts per candle as ordinates and candle power readings as abscissæ. The observations will then present much the same appearance as the bullet marks in a target. For this reason the result of plotting the determination in this way is called a target diagram. The bull's eye of the target is given by the rating of the lamp. Its coördinates, for example, might be 3.5 watts per candle, and 16 C.P. A rectangle should also be constructed representing the limits within which the lamp must come in order to be accepted.

The coördinates of the corners of this rectangle might be, for example:

3.9	watts	per	candle	18 C.P.
3.1	"	"	"	18 C.P.
3.9	"	"	"	14 C.P.
3.1	"	"	"	14 C.P.

Experiment 18. — Effects of Varying the Impressed Voltage on an Incandescent Lamp.

As the voltage increases from zero, the first effect is to decrease the resistance of the carbon filament; then the lamp begins to light up, and both the color and brilliancy of the light improve as the voltage goes on increasing. When the voltage is very high, the lamp gives an almost white light. Its efficiency in watts per candle power also improves. The objection to running lamps under these conditions is that the life is thereby shortened. The rated voltage of a lamp is therefore a compromise due to a consideration of the relative importance of color, candle power, efficiency and life.

Method. — Place the lamp to be tested in the photometer and increase the voltage by regular increments from zero until the lamp appears to be about to burn out, and the filament appears thick and intensely bright. Note the current corresponding to

each voltage. As soon the lamp becomes bright enough, begin to measure the candle power also.

Report. — Calculate the watts per candle and the resistance of the lamp for each set of observations. Construct the following curves on the same sheet of cross-sectional paper, the voltmeter readings being taken as the common abscissæ for all curves.

Candle Power	Watts per Candle
Resistance	Current.

Experiment 19. — Distribution of Light from an Incandescent Lamp.

In order to investigate the distribution of light from the bulb of an incandescent lamp, it is necessary to mount the lamp so that its candle power may be determined when it is turned through different angles about a horizontal axis. The axis in question must pass through the center of the spherical part of the bulb. In changing the angular position, care must be taken to keep this axis at a fixed distance from the standard lamp.

Before beginning the experiment, place the lamp in a vertical position with the tip pointing upwards. Adjust its voltage until the candle power equals its rated value. Note this voltage and keep it constant throughout the test. Determine the candle power at eight different angular positions, taking in the entire hemisphere containing the tip. Plot the results in the form of a polar diagram, the radii being the candle power readings. Draw a curve through the observations when plotted.

Calculate the mean hemispherical candle power by averaging the readings obtained.

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